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**A Study of Binocular Vision using  
Visual Evoked Potentials**

(誘発電位による両眼視機構の研究)

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## 「要約」

視覚誘発電位とは視覚刺激の出現、変化に対応して起こる頭皮上の電位の変化（脳波）である。この手法は、現在、実用化されている手法としては、人間の視覚機能に関するほとんど唯一の生理的指標である。特に、両眼視機能に関する誘発電位は、大脳からの信号を選択的に記録できるという利点があるにもかかわらず、これまであまり多くの研究が行われていない。

現在視覚研究室では、視覚誘発電位を用いて、人間の視覚機構、とりわけ立体視、運動視にかかわる機構の解明のための研究を進めている。このテクニカルレポートでは、そうした努力の一部として両眼視誘発電位に関して最近行った三つのプロジェクトの概略を紹介する。

### （１）誘発電位記録環境の整備

今回行ったような実験では、条件間の変動を少なくするために、多くの条件をランダムな順序で行い、記録された脳波信号を条件ごとに仕分けしてアヴェレージすることが必要である。刺激提示システム（マスコンプ、MC 5600）、パーソナル・コンピュータ（PC 9801）、脳波記録システム（日電三栄、7T18）を結合し、相互に通信し合うことでそうした機能を実現させた一例を紹介する。

### （２）色度ランダム・ドット・ステレオグラム

ランダムドット・ステレオグラムを用いた両眼立体視に関する視覚誘発電位については、ベル研の Julesz らの研究があるが、彼らはそうした誘発電位が記録可能であることを示しただけであり、それ以上の検討は行っていない。今回我々は、赤緑色度ランダム・ドット・パターンを用いて、両眼立体視における輝度情報と色度情報の役割の検討を行った。現在までに、ランダム・ドット・パターンを等輝度としたときには、立体視が消失はしないが非常に観察し難くなり、またそれに応じて誘発電位もほとんど認められなくなることを明らかにした。

### （３）運動サイン縞パターンの両眼加重

大沢ら（1986）は、ネコの両眼に反対方向に運動するサイン縞（サイン波状に輝度の変化する縞パターン）を別個に提示すると、脳内で二つの刺激が合成されてコントラスト反転パターンとなり、反転パターンに対する誘発反応と類似の反応が得られることを示した。今回発表する実験では、この現象が、人間においても成立することを実証し、また両眼加算にあたっての周波数チューニング特性を測定し、この現象が両眼視機能の詳細な検討にあたって、有効なツールとなり得ることを立証した。人間の両眼加算の周波数チューニングは非常にシャープであり、両眼の周波数を25%ずらすと反応は半分以下になる。

## Introduction

Visual evoked potentials (VEPs) are nearly the only electrophysiological technique readily available to study human visual functions. Of these, *cyclopean* VEPs are particularly useful because they are generated only when the two eyes are stimulated simultaneously, and hence allow us to study binocular mechanisms in isolation.

There are two methods to elicit such cyclopean responses. One is the type which utilizes dynamic random dot patterns (Julesz et al. 1978, 1980). In this type of stimuli, stereoscopic depth patterns are embedded in the correlation of randomly positioned dots in a pair of images, and these are invisible to us unless the two images are binocularly fused. Almost certainly, VEP responses generated by these stimuli must depend on stereoscopic vision and binocular fusion. The other method was developed recently by Ohzawa and Freeman (1986) with the cat. They used a pair of sinusoidal gratings drifting in opposite directions and presented them dichoptically to elicit cyclopean VEPs. Since the responses could be generated with horizontally oriented gratings which lack horizontal disparity, the responses are independent of stereopsis per se.

The results of these studies indicate the feasibility that specific aspects of binocular vision such as stereopsis, binocular fusion, and binocular summation may be studied in isolation by different types of cyclopean VEPs. These previous studies, however, did not go beyond basic demonstrations of the phenomena and feasibility of the approaches. With respect to dynamic random dot stimuli, the relationship of the responses to parameters such as dot size, size of disparity, size and form of depth profiles, dot patterns defined by equi-luminant colors, and temporal parameters are all unknown. With the opposite-drift grating stimuli, the responses have been demonstrated only in cats.

In this technical report, two VEP experiments using different types of binocular stimulation are described and a portion of results is reported. In the first experiment, VEP responses to chromatic dynamic random dot stereograms are recorded varying luminance contrast ratio. All previous VEP studies used random dot patterns defined by luminance, and it would be worthwhile to see if responses change when the dot patterns are defined purely by hue differences. The second experiment was conducted to demonstrate and utilize in humans cyclopean VEPs elicited by opposite-drift gratings.

The purpose of this report is to introduce VEP research activity at ATR Visual Perception Laboratory by presenting some preliminary data. This report is by no means final; both experiments are still on-going projects, and quantitative analyses of the data has not been conducted.

## General Method

### *VEP Recording*

Two adults were used as subjects, and standard procedures were used for recording visual evoked potentials. Briefly, three active electrodes were placed on the scalp: at 3 cm above (Oz), 6 cm above the inion (uOz), and at 3 cm above and to the right of the inion (O2). All these were referenced to an electrode placed on the right ear lobe. The other ear lobe was used for the grounding electrode. In addition to electroencephalograms (EEG)

recorded from these electrodes, electro-oculograms (EOG) of the left eye were also recorded to detect eye movements and blinks so that EEG records during saccades and blinks could be excluded from the analyses. Records of eye movements also allowed us to detect eye movements correlated with visual stimuli.

Signals from these electrodes were recorded by the system shown in Fig. 1. They were amplified and band-pass filtered to 0.3 - 30 Hz, and sampled and averaged by an evoked potential recording system (NEC-San-Ei, 7T18). Samples were taken at approximately 1 kHz. To achieve artifact rejection, the system was able to discard data from sweeps containing abrupt voltage changes, which indicate the presence of various artifacts resulting from eye movements, blinking, and muscle activities. Raw (un-averaged) EEG signals, EOG, stimulus sync, and other relevant data were also recorded on an FM tape data recorder for later off-line analyses.

### *Stimuli*

Visual stimuli were generated on a 19-inch CRT (66 Hz refresh rate) display driven by the Masscomp graphics system. Two stimulus fields were positioned side-by-side on the screen and viewed dichoptically via a periscope-type mirror setup. To separate the stimuli completely for the left and right eyes, an opaque septum was placed between the eyes.

We used two types of stimuli which might tap different aspects of human binocular vision (see Introduction). One was the dynamic random dot stereogram (Experiment I), and the other was the opposite-drift grating stimulus (Experiment II). An example from each stimulus type is shown in Figs. 2A and B.

Each monocular stimulus was presented in a 10x10 degree square. Each pixel of the display subtended a visual angle of 1.5 arc min. at a distance of 69 cm. For random dot stimuli, each dot was 2x2 pixels in size, and therefore subtended 3 arc min.

In order to counter variability inherent in neurophysiological responses, stimulus conditions for a series of measurements were interleaved randomly. For example, to obtain a spatial frequency tuning curve consisting of 5 points, all 5 stimuli were presented for about 20 seconds in a random order, and the entire set was repeated 10 to 20 times. In this manner, long- and short-term variability of neural responses will be distributed evenly to all conditions, and hence can be made less likely to bias the results for a particular condition. A "null" stimulus consisting of uniformly bright fields for each eye was included in a randomized stimulus set to estimate residual background activity of the EEG after averaging.

### **Experiment I: Dynamic Random-Dot Stereograms**

The primary purpose of this experiment is to evaluate the effect of luminance contrast on VEP responses elicited by an abrupt change in cyclopean depth using chromatic dynamic random dot stereograms. Although the presence of depth perception in isoluminant stimulation is controversial (see Livingston and Hubel, 1987), all previous VEP studies using dynamic random dot stereograms employed only luminance patterns (e.g. Julesz et.al., 1980). This experiment is conducted to see if there is any change in VEP responses when the luminance contrast of chromatic random dot stereograms is varied.

### Method

With the stimulus shown in Fig. 2A, the binocular fusion of the two fields allows cyclopean perception of a checker-board pattern in depth. This perception results from small binocular disparities embedded into the image pair as a small lateral shift of dot pattern. Fig. 2A, however, is only a (static) frame from a sequence of frames used for stimulation. Since no VEP may be elicited by a static stimulus, temporal changes in the stimuli are necessary to evoke a response. The size of binocular disparity, hence the amount by which the checks appear to extrude from other checks, may be varied by changing the amount of shift of dot patterns. However, if we use the same dot pair and simply vary the amount of shift in time this change will not be cyclopean, since the change will be visible monocularly as a sudden movement of regions of dots. What causes responses arising from such a change is not clear; they could be due to lateral motion of dots as well as to changes in the depth profile.

This problem can be solved by using dynamic random-dot stereograms (Julesz, 1971). Since there are an infinite number of different dot patterns to create the same cyclopean pattern (in this case, a checker-board pattern), dot patterns themselves may be changed quite rapidly without changing the depth profile as long as the size of shift and regions where shift occur do not change. Therefore, if dot patterns are refreshed rapidly and the changes in the depth profile occur only every once in a while, lateral shifts of dots will be completely invisible monocularly. However, a change in the amount of shift causes a change in the depth of checks, which in turn will cause corresponding changes in the depth profile. This change is cyclopean, and therefore may be used to elicit a VEP response.

Typically, in our experiments, the same dot patterns were maintained for 8 frame periods of the display raster (66 Hz). The depth profiles alternated between two patterns, but were kept constant for 8 refreshes of the dot pattern, and then changed to the other profile. Therefore, the cycle time of the depth profile change was 128 (8x8x2) frame periods which were approximately 2 seconds.

An example of a stimulus pair is shown in Fig. 2A. Each monocular pattern consisted of 200 x 200 dots, and each dot subtended 3 arc min. Responses are recorded to red-green stereograms and correlograms which contain a cyclopean checker-board pattern similar to that in Julesz et al. (1980). Each recording session was conducted using either stereograms or correlograms with five different luminance contrast levels including isoluminance. The luminance match of red and green dots was attained using minimum motion technique (Anstis and Cavanagh, 1983).

### Results

Results from subject TS are shown in Figs. 3A, B, and C. Fig. 3A and B shows the case where there was a disparity of 12 arc min. corresponding to a shift of 4 dots, while Fig. 3C shows the results from a control condition with no disparity. Fig 3A shows the waveform from a condition with high R/G luminance contrast, and Fig 3B is from isoluminance condition. For both, the cyclopean checker-board appeared only during the time (960 msec) indicated by high level shown in the top-most trace. During OFF period, a flat front parallel plane of dynamic dots was visible.

As for the high contrast condition (Fig. 3A), responses to depth changes of the cyclopean feature are clearly discernible. Responses are most apparent for traces indicated as Oz and O2 (see Methods) to the left of the waveforms. Positive (downward) going responses are clearly visible for onset and offset of cyclopean pattern with a latency of

approximately 200 msec. The response from the electrode at uOz is smaller although transient responses to the onset and offset are detectable. In isoluminance condition, however, the responses to the depth change are not clearly visible. Some transient component seems to exist, especially for the onset, but not as large as in the high contrast condition.

Fast variations with a period of 120 msec (8.3 Hz) are also apparent in these waveforms. These are the responses to refreshes of random dot patterns occurring at this rate. By using a rather low dot refresh rate, it is possible to evaluate separately the effect of the R/G luminance ratio on VEP responses elicited by depth changes and by pattern refreshes. It is notable that VEP responses for pattern refresh in isoluminance condition (Fig. 3B) are still clearly detectable and do not seem reduced as much as those for depth change, although quantitative analysis of frequency components has not been fully conducted yet. This suggests that the disappearance of responses for depth change is not caused by the change in visibility of dynamic random-dots, or lowered CFF at isoluminance. Additional experiments (data not shown here) indicated that increasing the luminance contrast either way ( $R>G$ , and  $R<G$ ) results in larger responses. Similar trends were observed with random-dot correlograms.

As a control to the above measurements, responses from each electrode were measured when there was no disparity change at 960 msec intervals. In other words, there was no depth change in the pattern and it was always perceived as a flat plane. One of the waveforms from control experiments is shown in Fig. 3C. Irrespective of luminance contrast, no down-ward (positive going) slow response is observed, but the responses to random dot refreshes (8.3 Hz) are noticeable. These results confirm the results of Julesz et al. (1978, 1980).

The present results indicate that VEP responses for depth changes mostly disappear when dot patterns are made isoluminant. Stereopsis in isoluminance is still a controversial issue in psychophysics. Some studies reported that it disappears at isoluminance, but others report it does not (see De Weert et al., 1983). It certainly becomes weaker, at least as a subjective impression, but never disappears. Results from 2AFC experiments have shown that the depth differences are still detectable at isoluminance (De Weert et al. 1983). In our isoluminant conditions, our subjects sometimes could see the depth, and sometimes could not. We found that fixation requirements had some effect on the subjective strength of stereopsis and VEP; when the subject was asked to fixate on a central fixation marker very carefully, the impression of stereopsis tended to be weaker, and the amplitude of VEP was smaller. To investigate this issue, further experiments combining psychophysical and VEP measurements are being attempted.

## Experiment II: Opposite-Drift Gratings

Ohzawa and Freeman (1986) have shown with the cat that it is possible to elicit VEP responses by dichoptic presentation of a pair of sinusoidal gratings drifting in opposite directions. Although these responses are cyclopean, they are independent of stereopsis because they can be generated with horizontally oriented gratings which lack horizontal disparity. The purpose of this experiment is to see if the same responses can be elicited with human subjects. If these VEP responses can be recorded, this technique will be useful to investigate cortical activities using VEP technique.

### Method

An example of the stimulus patterns used in this experiment is shown in Fig. 2B. The rationale as to why such a pattern may be used to elicit cyclopean VEP is as follows. There are a few points that must be mentioned at the outset. First, it is known from the Ohzawa and Freeman (1986) study with the cat that drifting grating (travelling wave) stimuli do not elicit VEP responses. On the other hand, counter-phased gratings stimuli (standing waves) evoke good responses. However, these two patterns are intimately related to each other by the following mathematical relationship;

$$2 \sin fx \cdot \cos wt = \sin( fx - wt ) + \sin( fx + wt ).$$

In other words, a counter-phase grating represented by the left hand side of the equation is equivalent to the sum of two drifting grating components each moving in the opposite directions.

Using the above relationship, the following hypothesis may be examined. We can decompose an effective stimulus (counter-phased grating) into two ineffective stimuli (drifting gratings), and introduce each component separately through different eyes and recombine the two signals inside the brain. Is it then possible that the resultant neural activity after recombination can be effective again for eliciting a VEP? Examination of such a hypothesis is not merely a mental exercise, but provides important information as to how the visual cortex might combine two nearly independent input images from the eyes. Specifically, if such a response may be generated, it would mean that there is a mechanism which sums input from the two eyes *linearly* in the human visual system.

Use of the above stimuli for humans requires some modification. Because the cats used as subjects in the study of Ohzawa and Freeman (1986) were anesthetized and paralyzed, experiments could be performed with full-screen gratings in each eye. However, drifting gratings are extremely strong stimuli for tracking eye movements. Since the phase relationship of input to the eyes is important for the generation of cyclopean VEP's, tracking eye movements must be prevented in humans. For this purpose, the grating pattern for each eye was split into 4 vertical strips, and neighboring gratings were moved in opposite directions so that the stimulus for tracking eye movements could be canceled for each image. Notice, however, that the corresponding regions for each eye contain gratings which are moved in opposite directions because the assignment of directions to 4 strips are complementary for the left and right images.

### Results

Using the stimuli shown in Fig. 2B, responses were measured for sinusoidal grating stimuli presented dichoptically. As a control measurement, responses were obtained for counter-phased gratings. The results are shown in Fig. 4. Approximately 3 cycles of nearly sinusoidal responses are clearly visible for all 3 VEP waveforms. The

period of the response is approximately 60 msec, half the period of the stimulus temporal cycle. This is the typical pattern of responses to counter-phase gratings (Apkarian et al. 1981; Freeman et al. 1983; Tyler et al. 1985).

For drifting gratings, the response pattern shown in Fig. 5 was obtained (subject IO). Fig. 5A shows the results when gratings were drifting in the same direction over corresponding regions in each eye. The top 2 traces show responses to 2 spatial frequencies (5.0 and 1.25 c/deg from top, respectively), and the bottom trace shows the response to a null stimulus (contrast = 0). Apparently, as expected, no responses are detectable. However, when the grating are drifted in opposite directions, clear responses are generated as shown in Fig. 5B. The results show that this type of cyclopean VEP first demonstrated in cats (Ohzawa and Freeman, 1986) can also be elicited in human subjects.

Next, it is of interest to examine how close the spatial frequencies of the gratings presented to the two eyes must be in order to evoke responses. If the responses are indeed generated by the re-synthesis of a neural activity corresponding to counter-phase gratings from two drifting gratings, the frequency of the two gratings would have to be matched closely, as observed from the mathematical relationship presented above (see Methods). To examine this, 5 different spatial frequencies (0.91, 1.05, 1.25, 1.53, 2.0 c/deg) were presented in a randomized order to the left eye, while the right eye viewed the pattern of a constant spatial frequency (1.25 c/deg). Results are shown in Fig. 6 for subject IO. The spatial frequency of the grating presented to the left eye is indicated to the left of each waveform, and as with the previous figure, the response to the "null" condition is given in the bottom trace. Note that the largest response is generated for the condition where the spatial frequencies are matched for the two eyes (1.25 c/deg). As the mismatch is increased, the response is reduced. The degree of this reduction, hence the band width for the spatial frequency matching, is quite narrow. Although detailed analyses have not been completed, a 25% mismatch in the frequency reduced the response to less than a half of the peak response. This pattern of response and the narrowness of tuning was replicated in another subject (TS).

The opposite-drift gratings technique produced remarkably narrow spatial frequency tuning characteristics of cyclopean VEPs. For the purpose of comparison, an example of human psychophysical contrast sensitivity function is shown in Fig. 7 together with the tuning for the matching requirement obtained in the present study. Tuning functions of VEPs elicited by counter-phased gratings are much wider and quite similar to that of psychophysical contrast sensitivity. Cortical neurons, however, are known to exhibit quite narrow spatial frequency tunings (e.g. Movshon, 1978; DeValois et al., 1981) which are comparable to the present matching result. In this respect, therefore, the cyclopean VEPs elicited by grating stimuli are likely to be a reflection of the spatial frequency tunings of neurons in the visual cortex, because this response cannot be generated without active binocular interactions one way or another. These features indicate that cyclopean VEP's can furnish probes to study visual systems more intimately than other types of VEPs.

## Conclusion

We have shown in this project that the two types of cyclopean VEPs are indeed promising as tools for studying human binocular mechanisms. Particularly, we have demonstrated that chromatically defined dynamic random dot stereograms and correlograms would be useful for studying contributions of luminance and chromatic channels in the human visual system. The second method using opposite-drift grating stimuli gave the first demonstration of the feasibility of this method in humans.

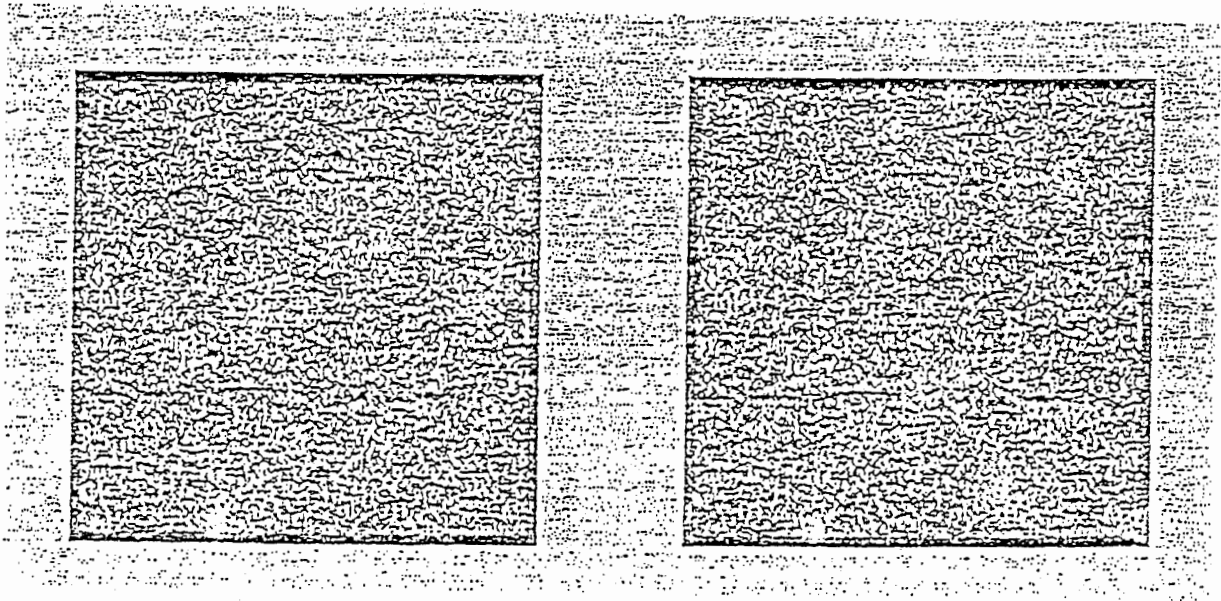


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A



B

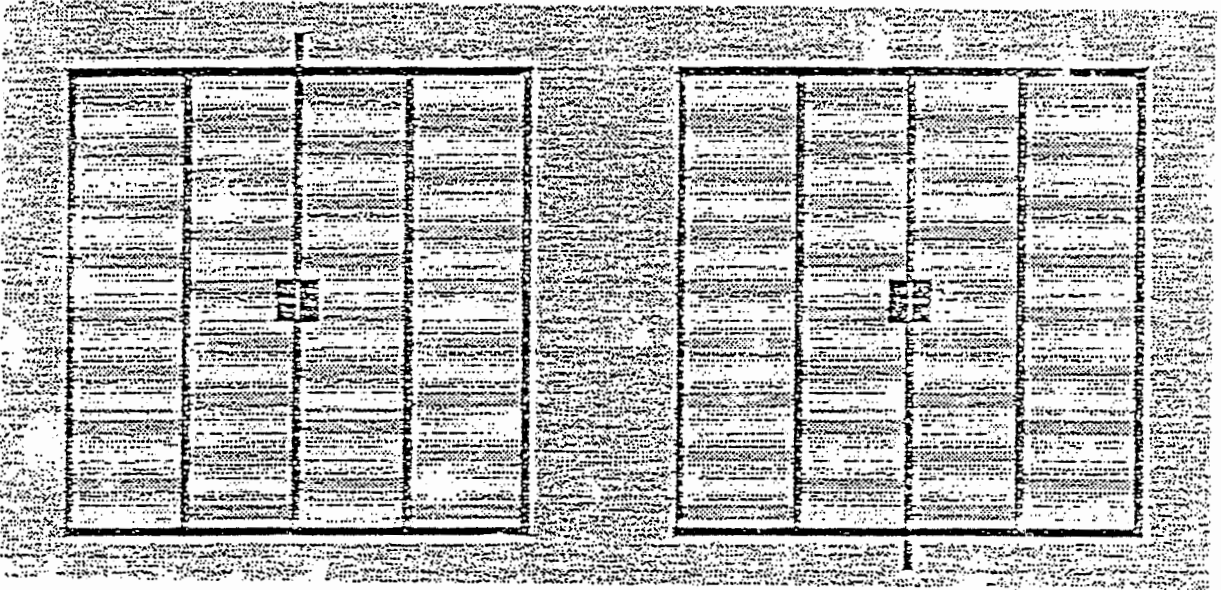


FIG. 2 STIMULI FOR CYCLOPEAN VEP'S

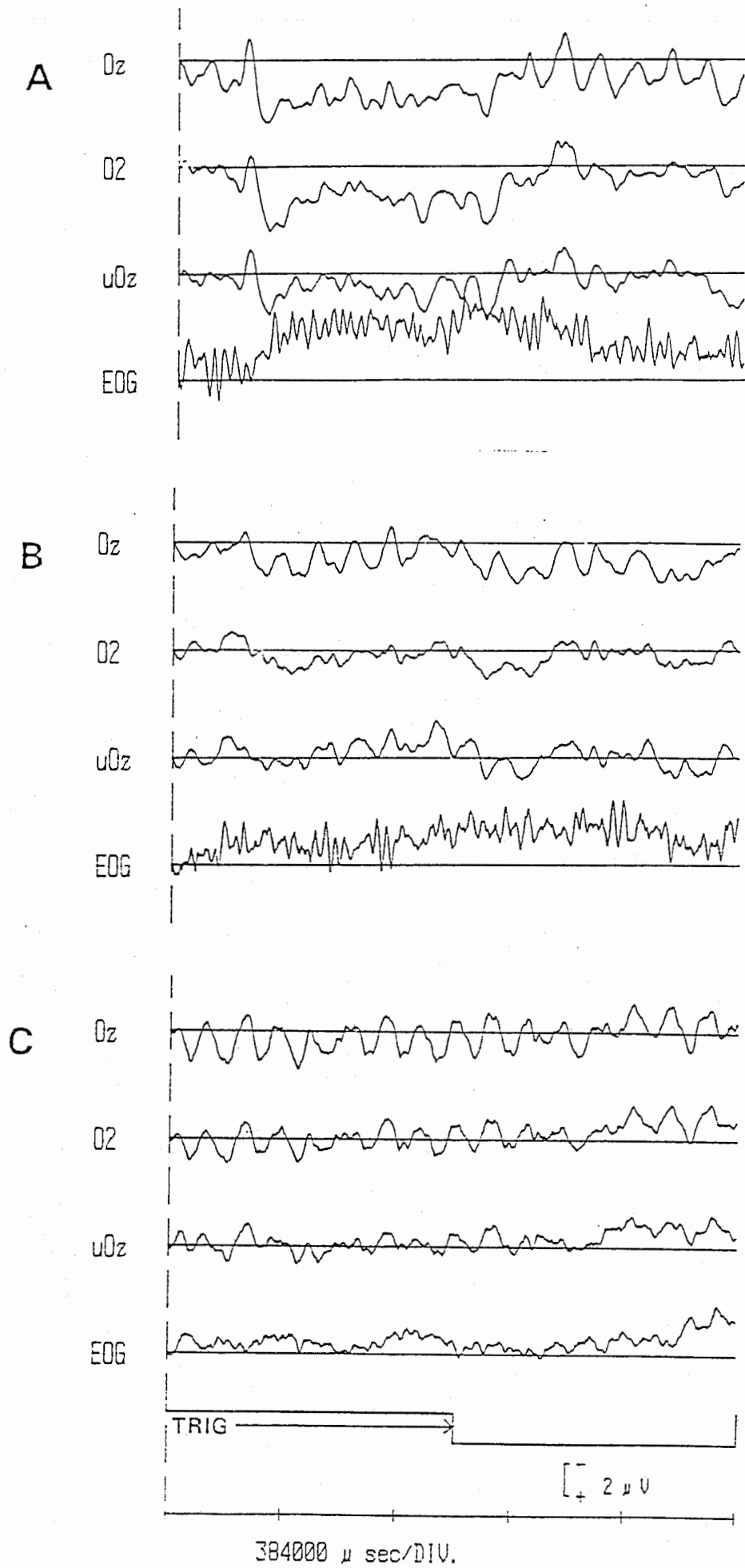


FIG.3 RESPONSES TO RANDOM DOT STEREOGRAMS  
 (A) high luminance contrast with disparity (B) isoluminant with disparity (C) high luminance contrast without disparity

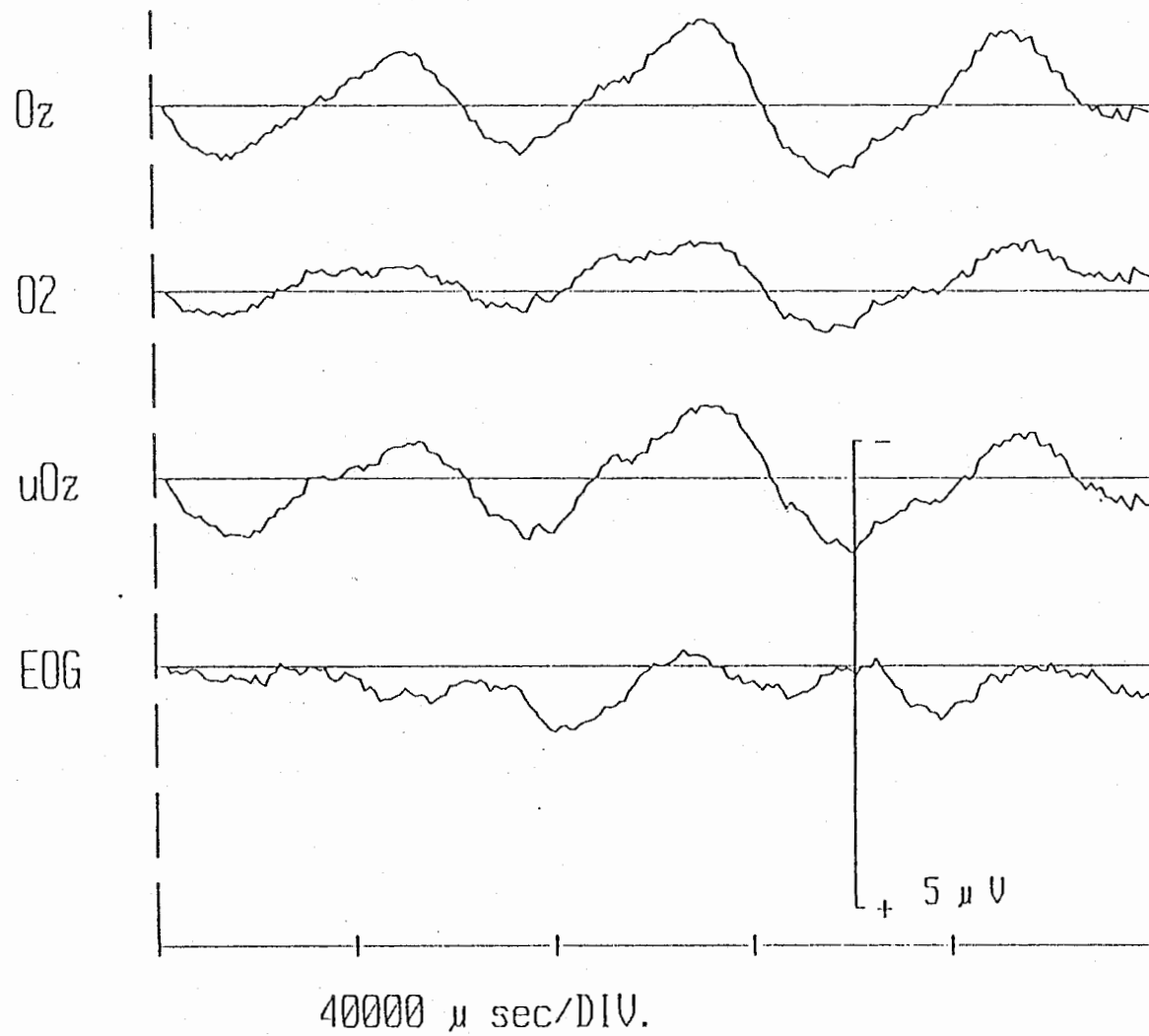
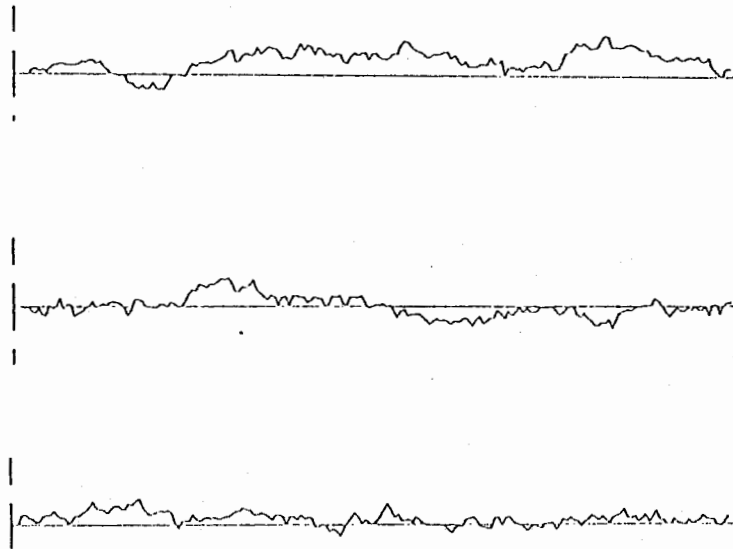


FIG. 4 RESPONSES TO COUNTER-PHASES GRATINGS.

**A**  
SAME DIRECTION



**B**  
OPPOSITE DIRECTION

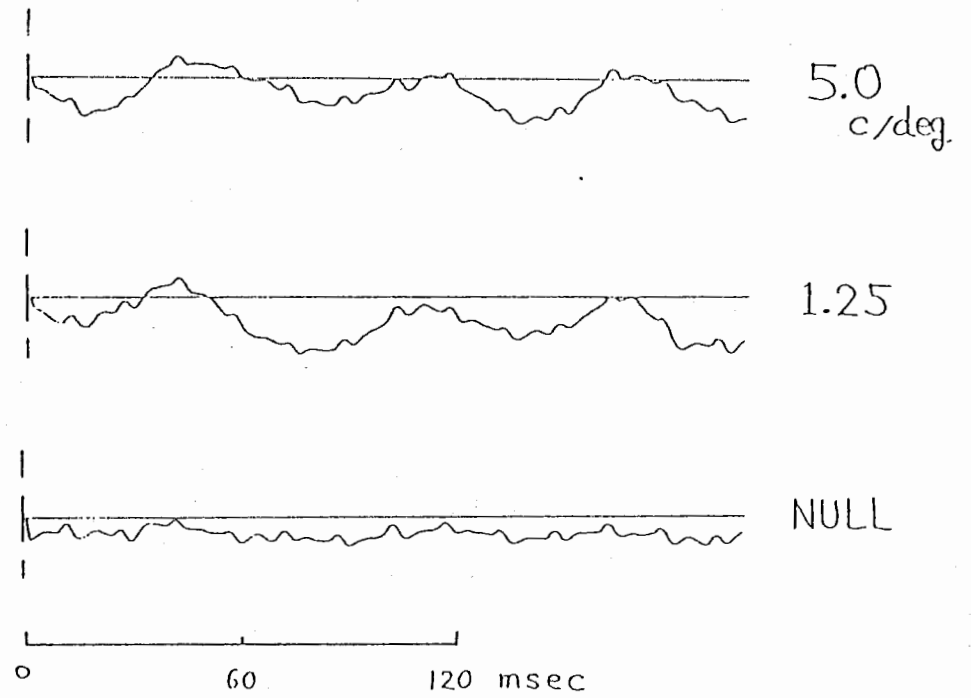


FIG. 5 RESPONSES TO DICHOPTICALLY PRESENTED DRIFTING GRATINGS.

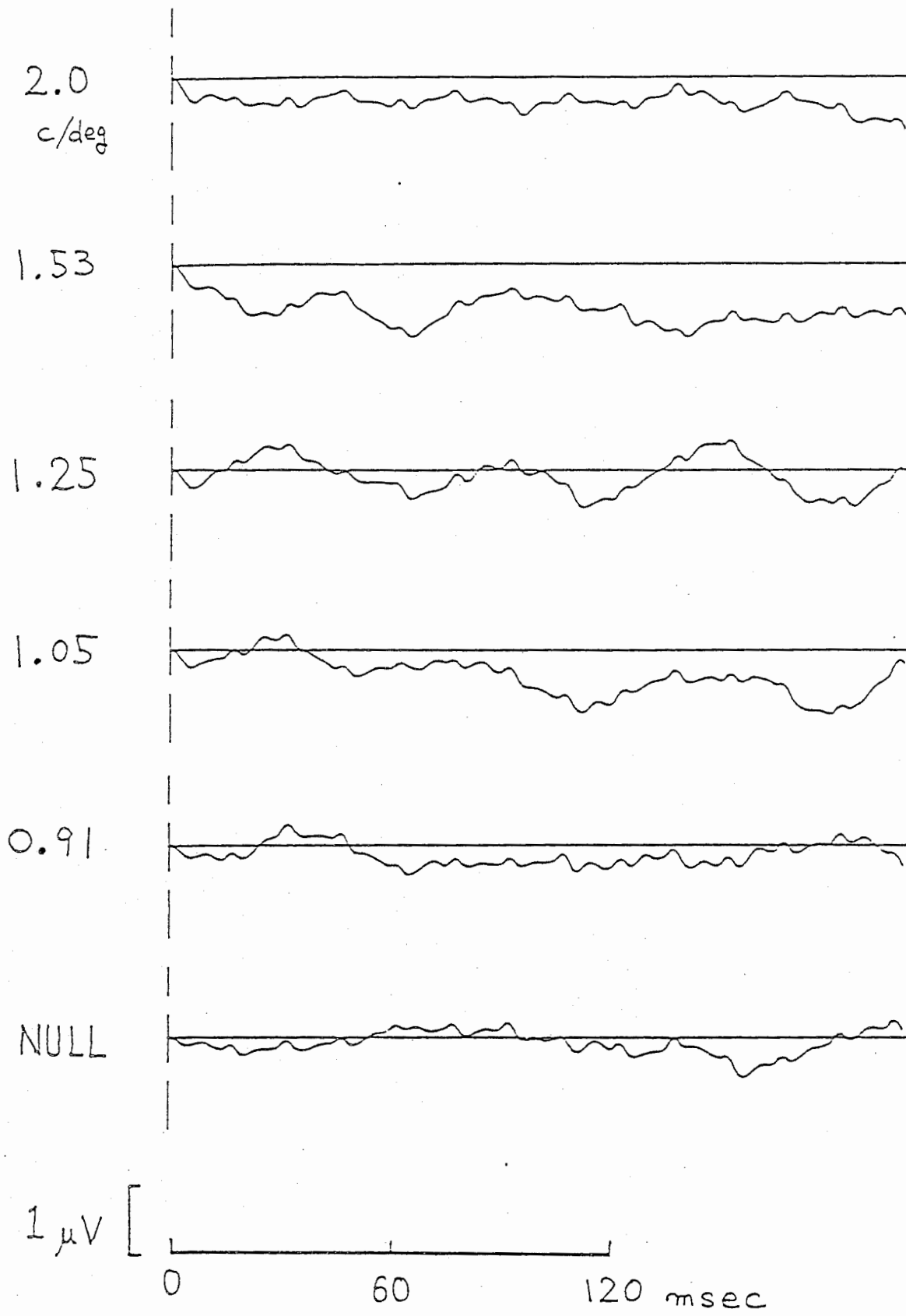


FIG. 6 SPATIAL FREQUENCY MATCHING REQUIREMENT FOR DRIFT VEP.

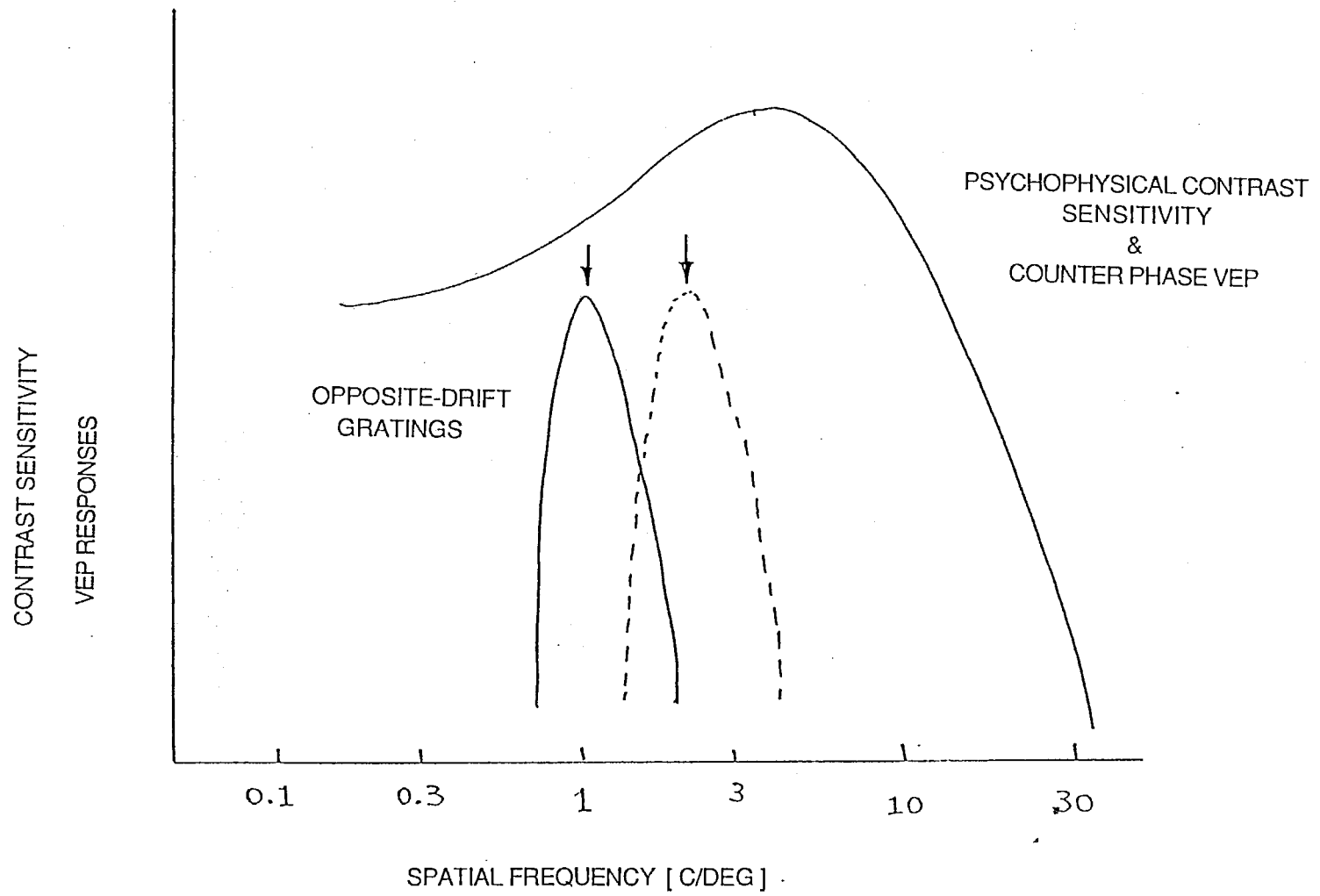


FIG. 7 COMPARISON OF SPATIAL FREQUENCY TUNING CURVES.