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Effect of Contrast on Fusional Visual Evoked Potential (VEP): A Model and Experimental Results

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ABSTRACT

A visual evoked potential (VEP) component that appears in the power spectrum only during binocular fusion has recently been discovered. When both eyes are stimulated with the same checkerboard but at different pattern reversal rates, this fusional component appears at a frequency intermediate between the two stimulus frequencies. We have proposed a model to explain the appearance of this intermediate component and have tested the model's predictions that the fusional component will remain constant independent of binocular or monocular changes in stimului contrast. As predicted by the model, changes in contrast over the range of 10 to 90% produced no significant change in the power of the fusional component.

Key Words: visual evoked potential, fusion, Fourier, binocular vision, dichoptic stimulation

In recent years many investigators have sought to use VEP's for the objective evaluation of binocular function. Binocular function may be evaluated by comparing binocular with monocular responses to the same stimulus, i.e., dioptic stimulation.[1,2] Dichoptic stimulation permits objective measurement of interocular suppression. In both flash VEP[3] and pattern-appearance VEP,[4] a varying stimulus was presented to one eye while a stationary pattern was presented to the fellow eye. Increased contrast of the stationary target resulted in decreased VEP response to the time-varying stimulus. Using polarized filters rotating at different rates in front of each eye, Lennerstrand[5] stimulated both eyes dichoptically with different pattern reversal rates. Lennerstrand and Jakobsson[6] then used that dichoptic stimulus to study the effect of fusion on the VEP and found that binocular interaction was the same for fused as for unfused images. However, they examined only VEP responses that were locked to the two monocular triggers.

Oguchi et al.[7] used electronic dichoptic stimulation in which each eye was stimulated by the same spatial pattern (checkerboard) but at different pattern reversal rates, and analyzed the VEP's with a Fourier processor. In the absence of fusion, two significant components, at frequencies corresponding to the stimulus frequencies used, appeared in the power spectrum derived from binocular VEP. In the presence of fusion, an additional response component, always situated between the two monocular components, was observed. Furthermore, a corresponding perceptual change, to a frequency be-

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tween the frequencies actually presented to each eye, was reported by the subjects. This additional component could not have been an artifact of recording, because it was not found in subjects who lacked stereo vision, and could not be obtained in subjects with normal binocular vision when fusion was broken by prisms.

We have proposed a model that explains the appearance of this intermediate frequency component and have tested the ability of the model to predict results in further studies on the effect of contrast on the fusional component of binocular VEP.

THE MODEL

Fig. 1 presents a mechanism for obtaining an intermediate frequency component in an electronic system. We used this system as a model of the visual system under binocular fusion conditions.

The binocular interaction is represented by multiplication of both eyes' signals. The multiplied signal:

$$\cos \omega_1 t \cdot \cos \omega_2 t = \tfrac{1}{2}[\cos(\omega_1 + \omega_2)t + \cos(\omega_1 - \omega_2)t]$$

can be described as a sum of two sinusoidal components. If the frequencies of the two input signals are close, i.e., $\omega_1 \simeq \omega_2$, then:

$$\omega_L = \omega_1 - \omega_2 \ll \omega_1 + \omega_2 = \omega_H$$

Cos $\omega_L t$ represents the low-frequency component and cos $\omega_H t$ represents the high-frequency component.

The multiplication of the signals is gated by fusion, i.e., the signal can propagate through the rest of the system only under fusional conditions. After the signal is transferred through a high-pass filter that blocks the low-frequency component and transmits the high-frequency component, $\cos(\omega_1 + \omega_2)t$, the signal is passed through a frequency divider that yields the required intermediate components at

$$\omega = \frac{\omega_1 + \omega_2}{2}.$$

The multiplication can be achieved with any nonlinear operation such as switching of the signal from one eye by the signal from the other eye.[8] High-pass filtering can easily be realized with a capacitance. Frequency dividing by two is commonly achieved in electronic circuits with a T-type bistable multivibrator (T-type flip-flop). A flip-flop can be in either of two stable states.[9] In the nervous system a flip-flop can be formed by two neurons connected by inhibitory synapses; this mechanism has frequently been proposed as a neural memory element, analogous to the use of flip-flops in computers. Flip-flop is also used to describe motor-neural mechanisms.[10] A T-type flip-flop changes its state for every rising edge in the input signal, dividing the input frequency by two. Since the output can be only one of two values, the output signal becomes a square wave of constant amplitude at the intermediate frequency

$$\omega = \frac{\omega_1 + \omega_2}{2}.$$

The flip-flop thus serves as a hard limiter as well as a frequency divider.

In the model, the direct channels from each eye to monocular cells in the cortex represent the pathways for the monocular components in the power spectrum. These components are independent of fusion.[6]

The proposed model can explain the appearance of the intermediate frequency component noted by Oguchi and co-workers.[7] Because the

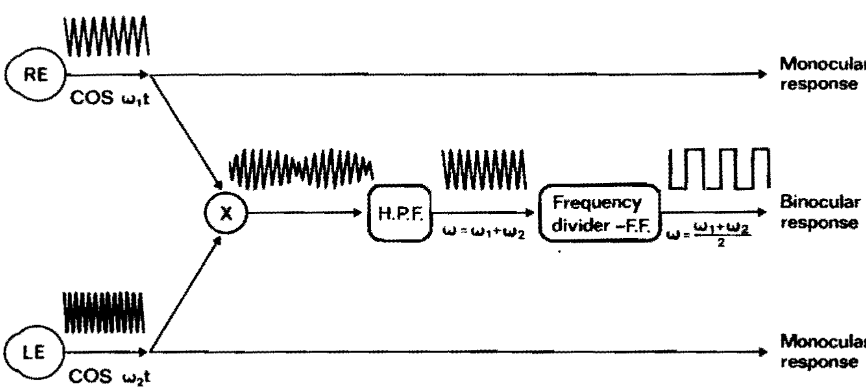

FIG. 1. Schematic diagram of a model of the visual system producing an intermediate frequency in binocular VEP. Under fusional conditions the multiplied signals from both eyes are shaped by the high-pass filter (HPF) and the frequency divider (F.F., Flip Flop). The output signal is a square wave of constant amplitude at the intermediate frequency.

usefulness of a model is determined by its ability to predict results, we conducted experiments to test two of the model's predictions.

Prediction 1: Our model predicts that the power of the intermediate component will be constant despite changes in the magnitude of the stimuli, because the output of the flip-flop is always of constant amplitude. The power of the monocular components, on the other hand, should increase monotonically with increased contrast of stimuli. We changed the contrasts presented simultaneously to both eyes, and measured the magnitude of the intermediate component, as well as the magnitudes of the left and right eye components as a function of contrast.

Prediction 2: If the contrast presented to each eye is different, interocular suppression and rivalry phenomena[3,4,11] would be expected to result in reduction of the response component of the eye presented with the lower contrast. Our model predicts that the intermediate component, however, will remain constant despite differences in the magnitude of stimuli presented to each eye, as long as fusion is maintained. We varied the contrast presented to one eye while maintaining a constant contrast for the other eye.

METHODS

Fig. 2 shows a schematic diagram of the system used for stimulation and recording of binocular fusional VEP. A pair of polarized filters was placed just in front of the left and right halves of the television screen; the axes of the polarizers were horizontal and vertical, respectively. A pair of fusional targets was mounted in the center of each polarizer. The subjects wore vectographic spectacles with polarized lenses whose axes coincided with the respective axes of the filters in front of the screen. Thus, the subjects could see only the right half of the screen with their right eye and only the left half with their left eye. Subjects with normal binocular function could sometimes fuse the central fusional targets. However, addition of a base-out prism made it much easier for the subject to maintain the fusional state. Checkerboard pattern reversal stimulation (20 min arc) at different reversal frequencies was generated on each half of the television screen (Medelec Visual Stimulator). Thus, each eye was stimulated with a different temporal frequency but identical spatial frequencies. Original mean luminosity was 50 cd/m^2, but the polarized filters reduced it by about 1.0 log unit. VEP's were recorded from an active electrode placed 3 cm above the inion on the midline. Reference and ground electrodes were placed on the earlobes. The recorded signals were stored on magnetic tape for later analysis with the Fast Fourier Transform program. Each sampling section was about 5 s (256 samples at 50 samples per second). The Fast Fourier Transform was calcualted for each section, and results of 15 sections were averaged. The power spectrum obtained was graphed on an X-Y plotter. The subjects, ranging in age from 20 to 32 years, were four female volunteers with normal binocular function.

Two subjects participated in the first experiment. Contrasts of 5, 10, 20, 30, 40, 60, or 90% were changed simultaneously for both eyes. The pattern reversal rate was 12.6 reversals per second for the right eye and 14.6 reversals per second for the left eye. The amplitudes of the Fourier components appearing at these frequencies and at the intermediate frequency (13.6 Hz) were measured for all the contrast levels. The two halves of the screen were fused throughout the recording; fusion was indicated by small uniocular contours seen within the fused binocular stimulus field.

Three subjects participated in the second experiment. The contrast of the checkerboard pattern presented to the left eye was fixed at 30%, while stimuli were presented to the right eye at contrasts of 2, 5, 10, 20, 30, or 90%. The pattern reversal rate was 12.6 reversals per second for

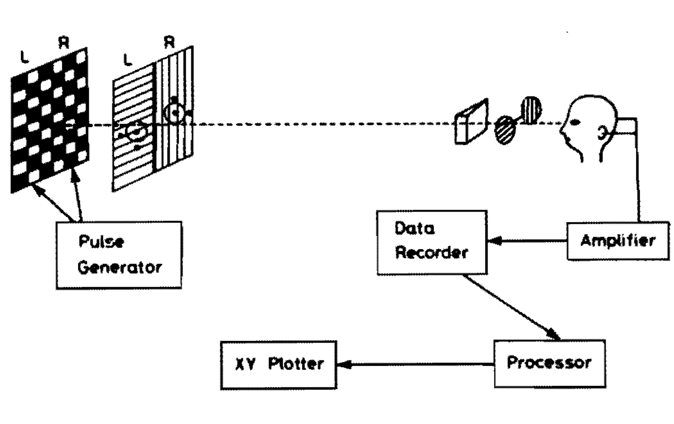

FIG. 2. Schematic diagram of the stimulus and recording system used for binocular VEP. The two sides of the screen are driven at different pattern reversal rates. The processor calculates the power spectrum of the recorded VEP.

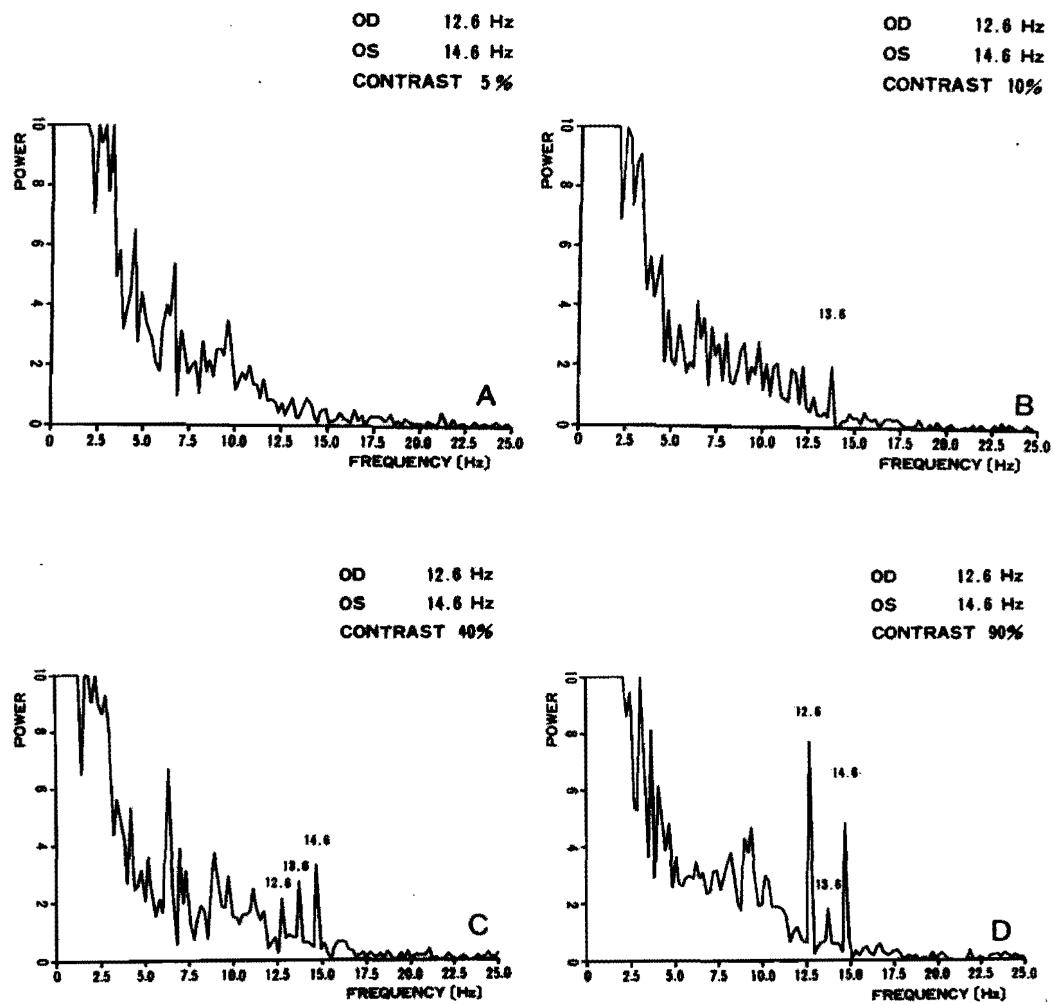

FIG. 3. Effect of binocular contrast changes on the monocular and fusional components of the VEP power spectrum in one subject. A: 5% contrast: neither the monocular nor the binocular component is seen. B: 10% contrast: intermediate component is clearly visible. C: 40% contrast: three peaks correspond to monocular and binocular components. D: 90% contrast: monocular components increase significantly, binocular component is unchanged.

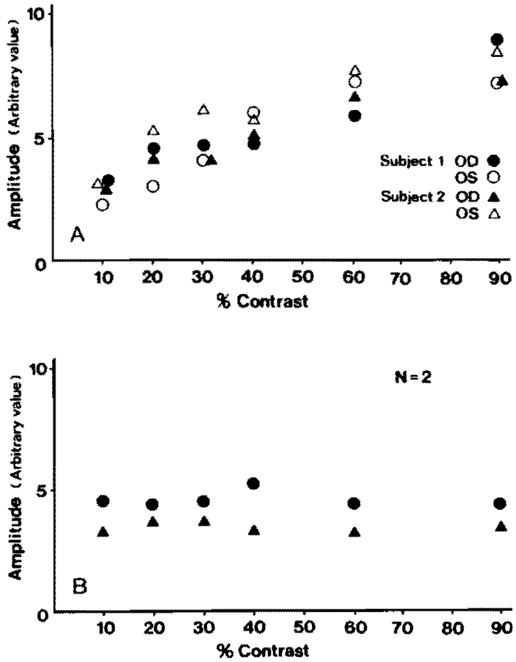

FIG. 4. Effect of binocular contrast changes on the magnitude of the Fourier components for two subjects (one represented by circles, the other by triangles). A: monocular components increase with increased contrast, showing saturation at higher levels. B: binocular fusional component remains constant.

the right eye and 9.6 reversals per second for the left eye. All subjects maintained fusion throughout the recording sessions.

RESULTS

In the first experiment (simultaneous contrast changes for both eyes), at a contrast of 5% (Fig. 3A), fusion of both halves of the screen was easily achieved, and all subjects reported a perceived change in frequency. However, on the power spectrum, there were no clear components corresponding to either eye, nor was the binocular intermediate component recognizable, due to the high noise level. At a contrast of 10% (Fig. 3B), a peak at exactly the intermediate frequency of 13.6 Hz was noted. As the contrast was increased, the components corresponding to each eye at 12.6 and 14.6 Hz increased also (Fig. 3, C and D). The magnitude of the monocular components increased monotonically with the increase in stimuli contrast (Fig. 4A). Only a slight effect of saturation[12] was noted. As predicted by the model, the binocular intermediate frequency component showed little change (Fig. 4B).

In the second experiment (contrast changes for one eye, contrast constant for fellow eye), subjects could fuse both halves of the screen despite the different contrasts and temporal frequencies presented to each eye. The power spectrum component corresponding to the constant 30% contrast stimulus presented to the left eye as a clear peak in all records at the frequency of 9.6 Hz. When a 2% contrast stimulus was presented to the right eye, no intermediate component or component corresponding to the right eye stimulus was noted (Fig. 5A), nor did the subjects report a perceived shift in frequency. When a 5% contrast stimulus was presented to the right eye, the intermediate frequency component became clear (Fig. 5B), and subjects reported a shift in frequency. The relative amplitude of the right eye component increased with increasing contrast (Fig. 6A). As predicted by the model, the magnitude of the binocular component remained constant (Fig. 6B). The results were very similar for all three subjects.

DISCUSSION

The model proposed here is a useful mathematical representation of signal flow and interaction in binocular cells in the cortex. The model is simple, analyzable, and consistent with the earlier findings of Oguchi et al.[7] It adequately predicted the effect of binocular and monocular contrast change on the intermediate component. The model does not conflict with current knowledge of the system, nor with the findings of others. Although Lennerstrand and Jakobsson[6] found no effect of fusion on the signals recorded under similar stimulus conditions, they used signal-averaging techniques locked to stimulus triggers and therefore monitored only monocular components.

Srebro[1] noted binocular facilitation of VEP when one stimulus was presented to both eyes. Our model predicts such a finding. Although the degree of binocular facilitation produced under such conditions has not yet been measured, we expect that under fusional conditions a constant, independent of stimulus contrast, will be added to the VEP amplitude produced by binocular stimulation without fusion. (Note that this comparison is not between monocular and binocular conditions, but rather between fused and unfused binocular stimulation.)

The purpose in normal binocular vision of the system described by this model should be further investigated. A hard limiter such as the flip-flop results in suppression of the signal when noise is increased. However, under certain conditions such as in a multiplier-type phase detector, a limiter can result in higher signal-to-noise ratio at the output than at the input.[13] Furthermore, Jaffe and Rechtin[14] have shown that a phase-locked loop preceded by a limiter could approximate, over a wide range of input signal and

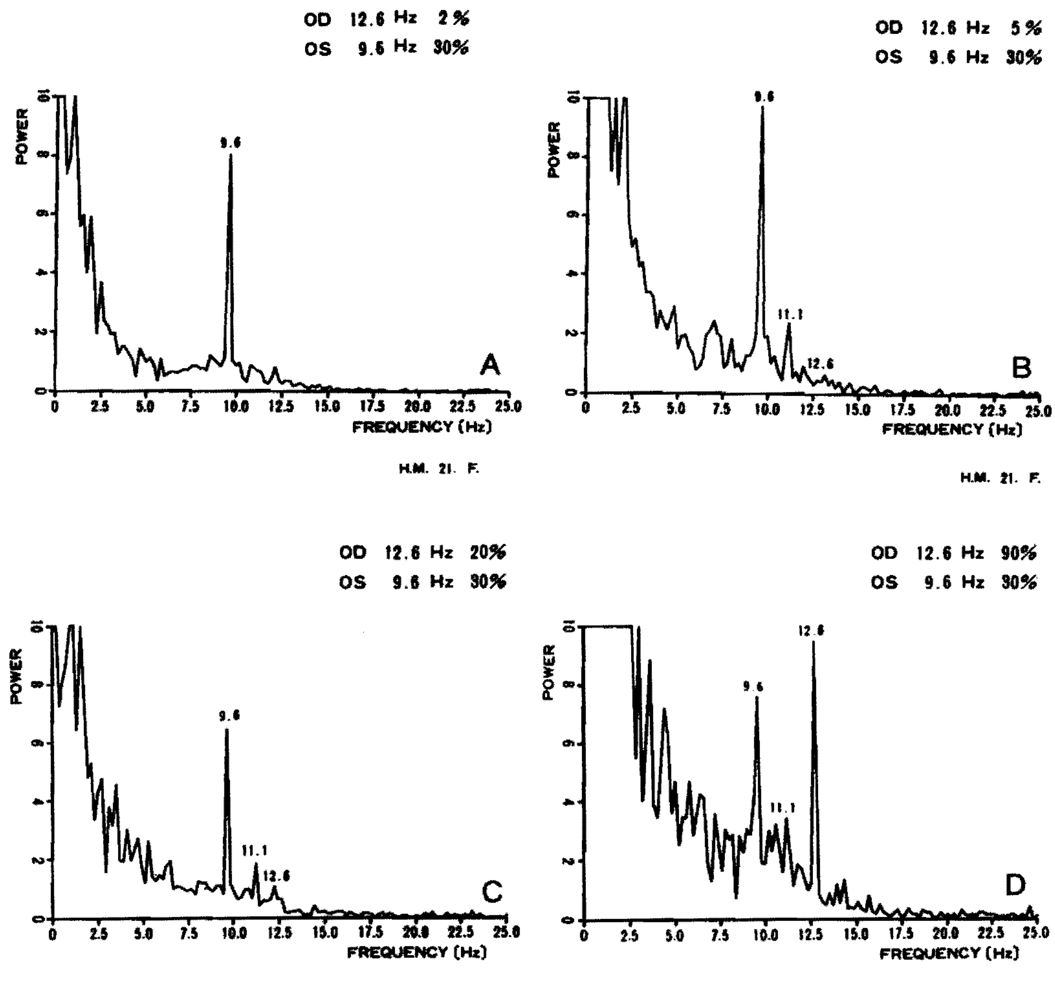

FIG. 5. Effect of varying contrast presented to the right eye while contrast to the left eye is constant at 30%. Results from one subject. A: 2% contrast: only left eye component is visible. B: 5% contrast: intermediate fusional component becomes clear. C: 20% contrast: right eye component is noticeable; intermediate component remains constant. D: 90% contrast: right eye component is larger than that of left eye, intermediate component remains constant.

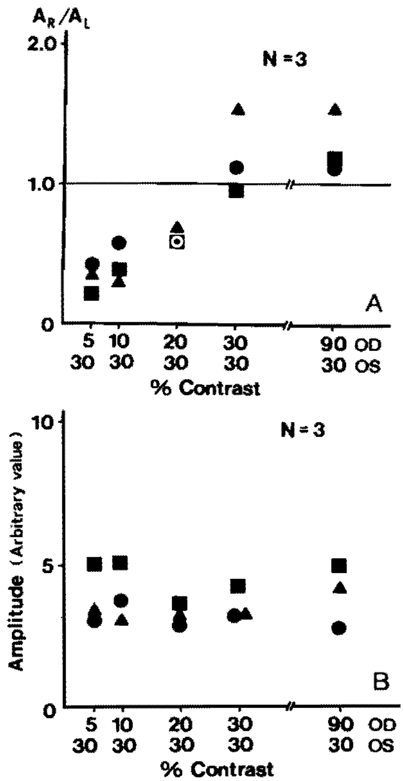

FIG. 6. Effect of varying contrast presented to the right eyes of three subjects (triangle, circle, square) while contrast to left eye is constant at 30%. A: ratio of the right eye component to left eye component increases with increased contrast. B: intermediate component remains constant.

noise level, the optimum performance that would otherwise be obtainable only with a more complex system of continually readjusted variable filters. A hard limiter, therefore, seems to be beneficial when it is followed with a phase detector. At least one such application can be hypothesized in the visual system. In the Pulfrich phenomenon,[15] signals from one eye are delayed by the neutral density filter, resulting in a phase difference between the eyes' signals. Thus, the phase relations between the monocular and the binocular signals can be used by the visual system to generate depth perception. The measurement of the phase relations will require some type of multiplication phase detector to follow the flip-flop.

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