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# Signal to noise ratio considerations in the analysis of sweep visual-evoked potentials

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More investigators are recommending rapid sweep displays to estimate visual-evoked potential (VEP) sensory thresholds. Theoretically, phase-sensitive analysis offers a higher signal to noise ratio (SNR) than phase-insensitive techniques and, therefore, a more reliable and equally valid threshold estimate. Phase-sensitive analysis assumes that the VEP phase does not change over the period of one sweep. This study tests the assertion that the VEP phase is sufficiently stable for valid and reliable phase-sensitive detection. Mathematical analysis shows that phase-sensitive detection yields a lower SNR than phase-insensitive analysis if the phase error is <45°. We recorded the VEP to contrast reversing sinusoidal gratings of sweeping spatial frequency (12.5–0.2 cpd) from 26 subjects. In most, phase varied >180° over one sweep. Moreover, these large phase shifts could not be diminished by modifying contrast reversal rate, direction of spatial frequency sweep, or sweep time. We conclude that when using spatial frequency sweeps, phase-insensitive detection is superior to phase-sensitive. The filter's bandwidth and the effect of SNR on sensory threshold estimations also are discussed.

## I. Introduction

Synchronous detection of VEP response to swept visual stimuli was first proposed by Regan.[1] Nelson *et al.*[2] noted the signal to noise ratio (SNR) advantage of phase-sensitive synchronous detection over phase-insensitive detection and argued that visual-evoked potential (VEP) phase was sufficiently stable (changed <10°) to allow the use of the phase-sensitive method in swept stimulus recordings. Norcia *et al.*[3] showed large phase shifts in spatial frequency sweep VEPs and commented on the inappropriateness of the phase-sensitive method for this class of VEP analysis. In both cases, the SNR analysis was qualitative.[2–4] In this paper, we quantify the relative SNR behaviors of these techniques and extend Norcia *et al.*'s[3] observations by investigating phase shifts of spatial frequency sweep VEPs as they relate to interindividual variation, pattern reversal rate, direction of spatial frequency sweep, and sweep time.

In a typical sweep VEP experiment, the subject views a visual display with vertical sinusoidal gratings that are counterphase modulated at 5–25 reversals/s. At the same time, either the grating contrast or spatial frequency is swept continuously over some range. The recorded electroencephalogram (EEG) spectrum's strongest peak is at a frequency twice that of the stimulus alternation rate (the second harmonic). The EEG signal measured during a swept stimulus presentation may be written as

$$\mathrm{EEG}(t) = A_r x(t)\left\{\cos[\omega_c t + \theta(t)] + R\left(m\frac{\omega_c}{2}t\right)\right\} + n(t), \qquad (1)$$

where $A_r$ is a constant, $\omega_c$ is the temporal alternation rate (the second harmonic of the stimulus alternation rate), and $x(t)$ is the magnitude signal (which varies with the swept stimuli parameters). The noise in the system is $n(t)$. The phase $\theta(t)$ results in part from various physiological changes such as adaptation of neural mechanisms. $\theta(t)$ also is affected by the spatial frequency sweep because the response to different spatial frequencies is associated with different delays.[5] In addition, the continuous variation of the spatial frequency may result in some temporal frequency modulation of the response, accounting for part of the phase variations. The residual

$$R\left(m\frac{\omega_c}{2}t\right),$$

where $m = 1,3,4,5\ldots$ is composed of components at other harmonics of the stimulus that are filtered out by

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the bandpass filtering centered around $\omega_c$. The bandpass filtered signal is, therefore,

$$\mathrm{VEP}(t) = A_r x(t) \cos[\omega_c t + \theta(t)] + n(t). \tag{2}$$

The bandwidth of this signal is $B_T = 2W$, where $W$ is the bandwidth of the modulating signal $x(t)$, which is assumed to be bandlimited, and the bandwidth of $x(t)$ is a function of the length of the sweep. The longer the sweep time the narrower is the bandwidth of $x(t)$. $\mathrm{VEP}(t)$ is a double sideband (DSB) modulated signal.[6] We can write the bandpass filtered signal in the quadrature carrier form

$$\mathrm{VEP}(t) = A_r x(t)[\cos\theta(t) \cos(\omega_c t) - \sin\theta(t) \sin(\omega_c t)] + n_i(t) \cos(\omega_c t) - n_q(t) \sin(\omega_c t), \tag{3}$$

where $n_i(t)$ and $n_q(t)$ are the inphase and quadrature components of the noise, respectively. Synchronous detection (phase-sensitive) includes multiplication by $\cos(\omega_c t)$ followed by low-pass filtering of width $W$. The demodulated signal obtained this way is

$$Y_D(t) = A_r x(t) \cos\theta(t) + n_i(t). \tag{4}$$

For the ideal case where $\theta(t) = 0$ and assuming that the noise spectrum is flat within the limited bandwidth of the signal, the SNR for the detected signal is

$$\mathrm{SNR} = \frac{A_r^2 \overline{x^2}}{\overline{n_i^2}}, \tag{5}$$

where $\overline{x^2}$ and $\overline{n_i^2}$ are the variances of the signal and noise, respectively.

This SNR is the maximum possible and is equal to the SNR of the nonmodulated signal even though the bandwidth of the modulated signal is twice as wide. This superior SNR results from the complete elimination of the noise quadrature $[n_q(t)]$ power due to the incoherency of this component with the detector's local oscillator. Where $\theta(t) \neq 0$, the amplitude of the signal decreases by $\cos(\theta)$, and the SNR would be reduced by a factor of $\cos^2(\theta)$.

Phase-insensitive detection assumes the phase of the signal to be unknown. The signal is multiplied by sine and cosine waves both at frequency $\omega_c$. These products are then averaged over time. The amplitude of the response is calculated as a Pythagorean sum of the two components. The result is independent of the phase. Therefore, for the phase-insensitive detector, Eq. (3) may be reduced by choosing any phase. For example, for $\theta(t) = 0$, the inphase component is identical to the phase-sensitive detector output, whereas the quadrature component includes only the quadrature noise component $n_q(t)$. Therefore, the SNR is half of the SNR of the phase-sensitive detector in the ideal case. Thus, the phase-sensitive detector has a potential benefit of 3 dB in SNR compared with the phase-insensitive detector. To benefit from this potential SNR improvement, the phase error should be such that

$$\cos^2(\theta) > 1/2 \rightarrow \theta < 45°. \tag{6}$$

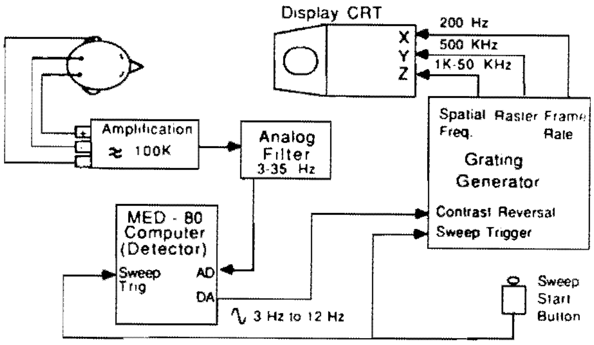

Fig. 1. Schematic illustration of the apparatus used to generate and record the swept spatial frequency VEP.

## II. Materials and Methods

Interindividual variation of phase-shift magnitude was investigated in 26 subjects. The effects of pattern alternation rate and sweep direction on phase-shift magnitude were determined on four subjects, and the effect of sweep time was evaluated on one of the four subjects. All subjects wore full optical correction, had 20/20 or better corrected visual acuity in each eye, and were free of any pathology or binocular anomaly. All subjects were tested monocularly in the interindividual variation experiment, and two of the four subjects were tested binocularly in the remaining experiments. (Binocularity appeared to have no significant influence on phase shift.) In each subject, phase-shift magnitude was quantified over that range of spatial frequencies where a significant VEP amplitude was evident. Informed consent was obtained from each subject before testing.

### A. Spatial Frequency Sweep Stimulus

Vertical spatial sine wave gratings were generated on a display monitor by analog methods. Using equations provided by Morgan and Watt,[7] we estimate that the grating contrast was 80% from 0.2 to 6 cycles per degree (cpd) and decreased gradually to 40% at 12 cpd. Gratings were drawn at a 200-Hz frame rate. Contrast reversal was controlled by an analog output from a Nicolet MED-80 computer. An electronic pulse initiated the sweeping of the grating spatial frequency and simultaneously triggered the acquisition of EEG data by the MED-80 (Fig. 1).

Stimulus variables in each experiment were as follows:

In the interindividual variation experiment, the field size was 20 × 15°, the mean luminance was 44.2 cd/m$^2$ (13 ft L), the spatial frequency was swept linearly from 12.5 to 0.2 cpd in 20 s, and the pattern reversals rate was 24/s (12 Hz).

For the experiment testing the effect of the pattern reversal rate, the rates tested were 6, 12, and 24 reversals/s (3, 6, and 12 Hz), field size was 16 × 12°, mean screen luminance was 23.8 cd/m$^2$ (7 ft L), and the spatial frequency was swept linearly from 0.5 to 12 cpd in 13 s.

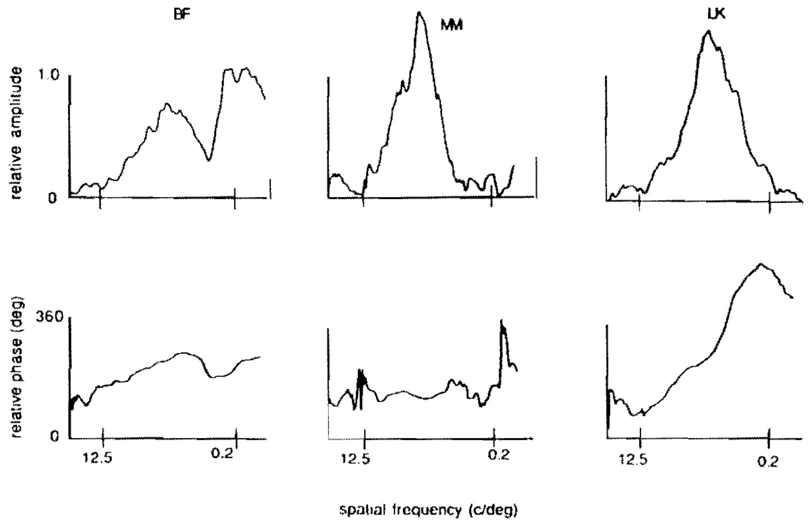

Fig. 2. Amplitude and phase plots for three subjects during a 20-s linear sweep of spatial frequency gratings from 12.5 to 0.2 cpd. The vertical bar at the end of each amplitude plot shows the 95% confidence interval of that VEP. Subjects BF, MM, and LK show typical, smallest, and largest phase shifts, respectively, seen in this subject population.

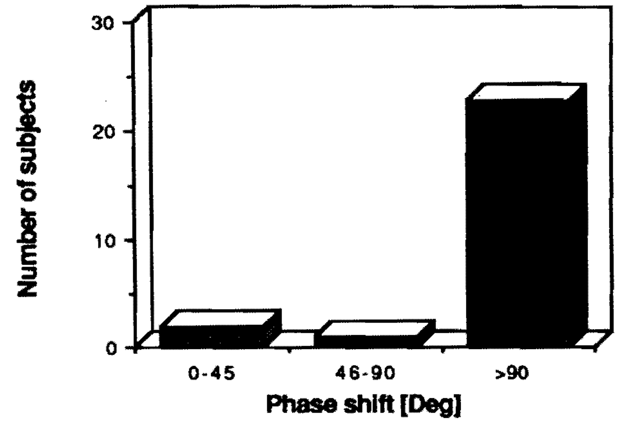

Fig. 3. Incidence of phase shift magnitudes for 26 subjects. Only two subjects had phase shifts of <45°.

To test the effect of spatial frequency sweep direction, the spatial frequency was swept both from 0.5 to 12 cpd and from 12 to 0.5 cpd. Pattern reversal rate was 12/s (6 Hz), sweep time was 13 s, field size was 16 × 12°, and the mean luminance was 23.8 cd/m$^2$.

To determine the effect of sweep length time, sweep times of 10, 20, and 40 s were tested, field size was 16 × 12°, the mean luminance was 44.2 cd/m$^2$, and spatial frequency was swept linearly from 0.5 to 12 cpd. Pattern reversal rate was 12/s (6 Hz).

### B. Evoked-Response Analysis

The EEG was derived from a bipolar electrode pair with the active at the Oz position, the reference electrode was 3 cm to the left of Oz, and the ground electrode was on the left earlobe. The amplified EEG was digitized at a rate of 16 samples/stimulus alternation cycle. The phase-insensitive detection was used to compute the magnitude with a low-pass filter of 0.5-Hz bandwidth. Sixteen sweeps were vector averaged for each subject in the intersubject variability experiment, and five sweeps were vector averaged in the other experiments. In each subject, total phase shift was quantified over that range of spatial frequencies where 0 $\mu$V was outside the 95% confidence interval of VEP amplitude[8] and where the plot of VEP phase vs spatial frequency was smooth and continuous.[3]

## III. Results

Large phase shifts were seen in spatial frequency sweep VEPs in the great majority of subjects and in all conditions under which the VEP was recorded.

The amplitude and phase plots of the VEP for the interindividual variation experiment are illustrated in Fig. 2. The amplitude vs spatial frequency profiles often have multiple peaks as reported elsewhere.[5] The phase plots show a large overall phase shift of more than 180° over the period of one sweep for most subjects. The degree of phase shift across spatial frequency varies greatly among normals (Fig. 2). This shift in individual recordings usually is composed of two elements: a slow and smooth shift over most of the spatial frequency range and a more rapid shift over a span of spatial frequencies where rapid amplitude changes are seen. Figure 3 shows the incidence of phase shift magnitudes for these 26 subjects. Only two subjects had phase shifts small enough (<45°) to warrant phase-sensitive detection.

The results of the other experiments are summarized in Fig. 4. Mean phase shifts at 24, 12, and 6 reversal/s were 192, 189, and 73°, respectively. All four subjects showed a smaller phase shift at 6 reversals/s. The mean phase shift was 189° for upward spatial frequency sweeping and 116° for downward sweeping. All four subjects showed less phase shift for downward sweeping. Subject GM showed phase shifts of 139, 163, and 232° for sweep times of 10, 20, and 40 s.

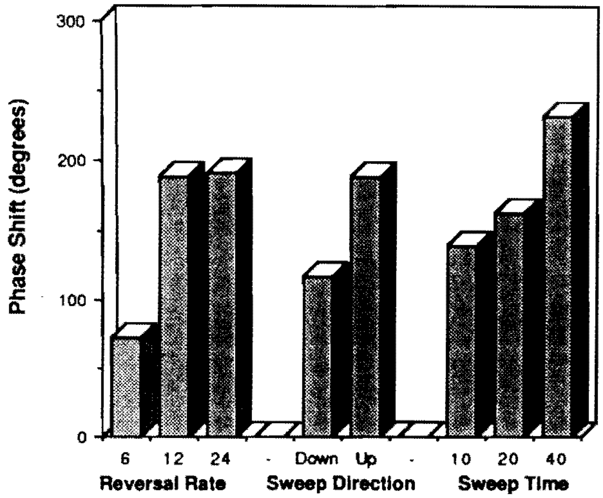

Fig. 4. Phase shifts remain large for all parameters tested: pattern reversal rates, sweep direction, and sweep time.

## IV. Discussion

Swept stimulus VEP methods are beneficial because they permit rapid evaluation of visual sensory thresholds. Such rapid measurements are especially important in the evaluation of small babies and other nonverbal, inattentive, or uncooperative patients. Synchronous demodulation techniques for the analysis of swept stimulus VEPs are advantageous because their fine frequency selectivity helps in rejecting noise. These techniques enable the implementation of such narrow filters, because filtration occurs after demodulation. Implementation of narrow low-pass filters is technically much easier than implementation of equivalently narrow bandpass filters.[2] The narrower the filter, the less noise gets into the system. However, the filter must be wider than the bandwidth of the demodulated signal $x(t)$.[9] Further improvement in the SNR is possible in the demodulation of a DSB signal by use of the phase information (when it is available) for phase-sensitive detection. To benefit from the potential 3-dB increase in SNR, the phase of the VEP should be accurate, and it should not change throughout the sweep period. Our results as well as others[3] indicate that the phase changes through a single spatial frequency sweep are usually >45°. These large phase shifts could not be diminished significantly by changing stimulus reversal rate, sweep time, or direction. Nelson *et al.*[2] used the phase-sensitive technique mostly for analysis of contrast sweeps rather than the spatial frequency sweeps (although they recommended it for both types of stimulation[2] and applied it both to spatial frequency and contrast sweeps[10]). The phase changes associated with contrast change are smaller than those observed during spatial frequency variations.[11] Thus the application of phase-sensitive detection to contrast sweep may be more appropriate than in the case of spatial frequency sweeps. However, Strasburger *et al.*[12] reported phase variations up to 100° during contrast sweep from 10 to 40%. A small portion of the phase shift we have observed may be due to the CRT-induced contrast reduction at higher spatial frequencies. However, spatial frequency variation still appears to be the dominant factor inducing VEP phase shifts, since large phase shifts are found at moderate to low spatial frequencies where stimulus contrast is constant. We presume that Nelson *et al.*'s[2] observation of minimal phase shift in swept stimulus VEPs was a consequence of a combination of factors: (1) low stimulus reversal rate that we have shown yields smaller phase shifts; (2) sweeping over limited range of stimulus magnitudes, such as high spatial frequencies or low contrasts only, and (3) an unintended selection of subjects with small VEP phase shifts. However, we feel that in general the use of phase-sensitive demodulation for spatial frequency sweep VEP analysis is not recommended, and the phase-insensitive analysis should provide more consistent SNR levels throughout the recordings.

The SNR will be affected not only by phase variation during the recording but also by the choice of phase. Even if the phase did not change during the recording, accurate matching of VEP and local oscillator phases is needed to benefit from the potential increased performance of the phase-sensitive detector. Nelson *et al.*[2] and Tyler *et al.*[13] claim that the threshold estimate obtained from the intercept of the linear regression line fit to the swept stimulus response is independent of the signal amplitude. Thus variations in VEP amplitude should not affect the expected threshold level defined by the intersection of the extrapolated slope with the base line. However, the reliability with which one can estimate the threshold from the measurement is highly dependent on the SNR of the measurement, since for any given noise level the intercept variability increases as the slope decreases. Because phase selection affects the slope of the amplitude function, the improper selection of phase even where VEP phase shifts are negligible will affect the reliability of the threshold estimate.

We feel that phase-insensitive analysis offers more consistent SNR levels for VEP sweep recordings, especially for the domain of spatial frequency where phase shifts are larger. Thus it should be the method of choice for most applications.

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most commonly used terms, phase-sensitive and phase-insensitive detection. In both methods, the signal is multiplied with a sinusoid of the carrier frequency and then low-pass filtered. For the phase-insensitive method, the magnitude measurement is independent of the phase. For the phase-sensitive method, magnitude measurement requires fixed and known phases.

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