Amplitude and phase characteristics of the steady-state visual evoked potential

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The amplitude and phase characteristics of the steady-state visual evoked potential (VEP) and grating perception were studied for an unbiased group of fifteen healthy female subjects. The variability of VEP data, as obtained by using a digital sweep technique, was high between subjects but relatively low within them. Earlier claims that psychophysical detection thresholds can be predicted from VEP amplitude values were confirmed, whereas no correlation could be established between amplitude values and the perception of suprathreshold contrast. By using a principle of minimum phase difference the importance of VEP phase as an indicator of data reliability and of perceptual encoding processes could also be established.

I. Introduction

The use and misuse of evoked potentials (EPs) as a diagnostic test is a matter of debate in the clinical literature. This is partly due to the use of EPs without a specific clinical indication, but also because of misconceptions of their diagnostic value and limitations as well as the absence of appropriate control values for comparison.^{1,2} Such a criticism does not question the important role which the application of EPs plays for the electrophysiological investigation of nervous function but draws attention to the necessity of experimental studies that contribute to more precisely showing the potentials and limitations of the EP method. The present study is meant as such a contribution concerning the use of EP as a tool for the noninvasive assessment of visual function.

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The most successful application of the visual evoked potential (VEP) is the measurement of the latency of the transient VEP for the diagnosis of multiple sclerosis (MS), a disease in which the visual pathway is frequently affected at a very early stage. The observed increase in latency is possibly related to intermittent conduction block within the demyelinated visual pathway.³ Another important case of visual pathology—and a potential application of evoked potentials—is that patients may have greater difficulties processing pattern information at suprathreshold contrast levels than can be explained by their performance on standard clinical tests (Snellen test chart, static perimetry). Such a discrepancy is often encountered in clinical observations of amblyopia, which is a frequent cause of visual impairment (see Ref. 4 for a review). A further application of VEP lies in the assessment of visual function in early childhood, which is important in the prevention of amblyopia (for a review see Ref. 5). Other sources of problems with the visual processing of suprathreshold patterns are lesions in occipital and parietal areas of the brain (see Ref. 6 for a review). This situation is not unlike that in audition, where difficulties in processing speech may not be predicted from the audiometric configuration alone.⁷ At this stage, however, there is no clear answer to the question of whether spatio-temporal visual function can more generally be assessed by means of VEP. This is why we decided to study the amplitude and phase characteristics of the steady-state VEP (SSVEP) and its possible relationships with aspects of visual perception. The SSVEP technique has been preferred to the more conventional transient VEP, since its higher recording speed allows a more thorough variation of visual stimulation parameters.

The interest of vision researchers in SSVEP dates back to the remarkable success of Campbell and Maffei⁸ who used a type of EP analysis invented by Keidel and Spreng^{9,10} for studying auditon (see also Ref. 11). The former workers measured cortical evoked potentials to sinusoidal gratings counterphased at a temporal rate of 8 Hz. By varying stimulus contrast and spatial frequency they found a linear relationship between the logarithm of the grating contrast and the (linear) amplitude of the SSVEP. This enabled them

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Received 9 June 1987.

^{0003-6935/88/061069-20\$02.00/0.}

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to predict the (psychophysical) detection threshold for grating contrast by means of linear regression. Campbell and co-workers¹² and Bisti and Maffei¹³ then used the same method for analyzing spatial vision in the cat where they established a close correspondence of VEP amplitudes and behavioral grating contrast sensitivities, and Maffei and Fiorentini¹⁴ showed the consistency of behavioral estimates of contrast sensitivities and results from single-unit recordings.

The contrast sensitivity function as derived from SSVEP measurements may be called the objective contrast sensitivity function (OCSF), and it is not because of difficulties to replicate the findings of Campbell and Maffei⁸ that its determination has not yet become a standard dignostic tool. Indeed, the conclusion of correspondence between the subjective and VEP threshold has been corroborated by a number of studies¹⁵⁻²² (for a review see Ref. 22). Rather it seems that the problem was technical. Establishing psychophysical detection thresholds for gratings by means of the extrapolation technique is a very time-consuming procedure if standard EP recording procedures are used, and this in turn results in a considerable variability of the data. This led many researchers to avoid the tedious regression procedure by simply using the interrelation between SSVEP amplitude and stimulus spatial frequency at a given stimulus contrast as a measure of grating visibility. This seemed justified by the numerous findings of unimodal VEP amplitude vs spatial frequency functions, which were often considered similar to the psychophysical CSF (see Ref. 23).

Difficult to reconcile with such findings was the fact that some authors reported the existence of bimodal SSVEP amplitude response functions at suprathreshold contrast levels in healthy subjects that otherwise showed no abnormality in their subjectively measured contrast sensitivity functions.²⁴⁻²⁸ More recent studies from the Smith-Kettlewell Institute confirmed this critical view.²⁹⁻³³

An additional problem for the use of SSVEP as a diagnostic tool was the observation that VEP amplitude data are intrinsically unreliable, whereas the variance of transient VEP latency had been found sufficiently small.^{34,35} This, however, does not rule out the SSVEP as a useful technique as its phase lag, being the corresponding parameter to the latency of the transient EP, has received little attention as yet. The reason for this is probably the fact that phase angles are only defined modulo 2π . That is, two given phase angles may be closer or farther apart, depending on whether one, or even several, phase revolutions of 360° occurred. For example, Levi and Harwerth (Ref. 36. p. 166) interpreted an increase of phase larger than 360° as significant without showing that a full revolution in phase actually occurred.

To investigate such inconsistencies in obtaining and interpreting SSVEP data we developed a digital sweep technique for recording and analyzing the SSVEP. This method is comparable to the analog sweep technique as used by Tyler et $al.^{25}$ (see Ref. 30 for a new version of their technique) and is described in detail elsewhere.³⁷ Its main advantage over conventional methods for VEP data acquisition is speed. The resulting reduction in recording time enables one to obtain the OCSF by means of the extrapolation technique from the data of one experimental session, and this improves the reliability of the results considerably. By using this digital sweep technique we studied amplitude and phase values of the grating evoked SSVEP response. Although a large part of this paper is devoted to describing the properties of the evoked response in its own right, the relationship between the SSVEP and grating perception is also of interest.

Method **II**.

We have developed a computer-based sampled sweep SSVEP acquisition system. The computer (an LSI-11/23) generated the stimuli, recorded the electroencephalogram (EEG), and performed the data analysis off-line. Details of this acquisition system are given in separate reports,^{37,38} and the principles underlying our analysis of the SSVEP have been discussed by Strasburger.^{38,39}

Stimulus Patterns and Procedure Α.

Temporally modulated vertically oriented sinewave gratings of variable spatial frequency and contrast were presented on either a HP-1310A display with a mean luminance of 17 cd/m^2 (up to Dec. 1983; see Fig. 3) or, when that unit went into repair, on a HP-1304A CRT display with 8 cd/m^2 . The displays were calibrated by measuring z-voltage/luminance interrelations for uniform test fields. This allowed us to adjust the dc levels and dynamic ranges so that the amplitude/luminance relationships were nearly linear up to 95% contrast. The digital resolution of the zmodulation functions and the size of the test fields were chosen so that the contrast at the highest spatial frequency used was not degraded (for details see Refs. 37 and 38). A frame rate of 64 Hz was used. Temporal modulation was a sinusoidal variation of local intensity with a frequency of 8 Hz (equal to sixteen reversals per second); that is, the stimulus intensity on the screen was given by

$$I(x,t) = I_{\text{mean}} \cdot [1 + C \cdot \sin(2\pi f_t t) \cdot \sin(2\pi f_x x)],$$

where x = horizontal spatial coordinate (deg), t = time (s),

- $I_{\text{mean}} = \text{space average luminance (cd/m²)},$
 - $C = \text{contrast} = (I_{\text{max}} I_{\text{min}})/(I_{\text{max}} + I_{\text{min}})$ $f_t = \text{temporal modulation frequency (Hz),}$

 - $f_x =$ spatial frequency (cpd).

The stimuli were grouped into sets of eighteen stimuli each, where individual stimuli differed in spatial frequency and sets differed in grating contrast. To realize the sampled sweep, the stimuli of a given set were presented one after the other for 3 s each with an interstimulus interval of 1 s during which the screen was set to the space average luminance of the grating stimuli. No EEG was recorded for the first second of each trial to allow the VEP to reach a steady state.

This allowed us to minimize a hysteresis from up and down sweeps, which occurs with a continuous sweep technique. Sweeps of increasing and decreasing spatial frequency values were used in alternation, and 3 +3 = 6 sweeps were employed during each experimental run. This resulted in a net presentation time of 12 s/stimulus or (at 8 Hz) $12 \times 8 = 96$ signal periods [corresponding to ninety-six periods on a computer of averaged transients (CAT)]. Such a recording totaled $18 \times$ 6×4 s = 7.2 min (4 s/trial), after which the subject rested a short time. Up to seven signal sets (see above) were given for the 3-D plots (Figs. 5 and 6) where the sets differed in stimulus contrast, and each such measurement was repeated at least once to allow the assessment of the reliability of the data and to balance temporal effects on the contrast variation. The maximum net recording time was thus $7 \times 2 \times 7.2 \min \sim 100$ min, including pauses for rest such a session lasted about twice this time. Both the spatial frequency and contrast variable were logarithmically scaled. The spatial frequency ranged from 0.5 to 25.4 cpd; the maximal contrast value was 40%.

Subjects viewed the screen binocularly from a distance of 128 cm, whereby the circular test field subtended 5 deg of arc in diameter. The stimulus display was surrounded by a moderately illuminated white cardboard screen of 1-m diameter. A small dot was positioned as a landmark in the middle of the test field. The subjects were instructed to avoid fixation and to use the dot merely as a center of attention with the gaze wandering around it.

B. Recording

A bipolar electrode montage was employed with one electrode placed midline 2 cm above the inion and the other on the forehead, two-thirds of the distance from inion to nasion. A symmetric placement was preferred over the more common lateral one to prevent the possible dominance of one of the two eyes. Grass gold cup-type electrodes with a modified lightweight shielded differential cable were used. The shield was connected to one ear.

C. Data Analysis

The EEG was sampled at a rate of 64 Hz. The offline extraction of the VEP from the sampled EEG comprised three steps: averaging over trials with a period length of 125 ms; a subsequent Fourier transform; and then vector averaging over spectral components of trials with identical stimulus parameters. For frequency components which are multiples of the stimulation frequency, this procedure is equivalent to a Fourier analysis of the raw EEG (see Ref. 39). Subsequently, only the 16-Hz component has been considered for analysis.

Mean values of phase and phase standard deviations were obtained by scalar averaging as defined in Strasburger (Ref. 39, p. 248). At a later stage of analysis it became clear that vector averaging (see also Ref. 39, Fig. 4) would have both been easier to calculate and for weak signals would have led to more consistent results. For higher signal levels, however, scalar and vector means yield similar results, so that a reanalysis of the raw data of the present experiment proved unnecessary.

All amplitude values in Sec. III are given in microvolts. Each amplitude plot contains an additional amplitude value obtained with closed eyes, which is taken as an indicator of noise, an assumption which is discussed in the Appendix. Continuous plots of temporal phase values were obtained by employing a principle of minimum phase difference. That is, phase values were assigned so that, by adding appropriate multiples of 360°, phase values of adjacent points had a minimum distance. The spacing of the sweep variable has been chosen small enough to allow the resolution of the ambiguity in selecting these phase values. (In the limit, zero spacing is equivalent to a continuous sweep, where the principle of minimum phase difference is unnecessary.) For a detailed discussion of our methods of analysis, see Strasburger.^{38,39}

D. Subjects

Fifteen emmetrope female students of medicine aged between 19 and 26 yr served as paid subjects. Male subjects were excluded from this study as preliminary experiments confirmed the view of Dustman *et* al^{40} that females generally display higher VEP amplitudes for the age group under consideration.

E. Contrast Sensitivity Function

Two kinds of (psychophysical) contrast threshold can be determined for counterphased sinusoidal gratings, namely, thresholds for seeing movement and thresholds for recognizing the pattern striation, that is, the spatial structure of the stimuli.⁴¹ Only pattern thresholds vary monotonously with the detection threshold for stationary gratings, whereas movement thresholds are typically lower at low spatial frequencies.⁴² Thus we decided to avoid the difficult task of using two types of threshold criterion with our unexperienced observers by simply measuring detection thresholds for stationary gratings at otherwise unchanged experimental conditions. Subjects were required to set the stimulus contrast to detection threshold by means of a hand-held potentiometer. In other words, a psychophysical method of contrast adjustment was used with the same experimental setup that served for the VEP recording. At least three settings were made to obtain the resulting average threshold value from which the contrast sensitivity was derived as the inverse threshold value.

III. Results: Amplitude Data

A. VEP Amplitude vs Spatial Frequency

The first experiment was designed to study the effects of stimulus spatial frequency and contrast on the SSVEP amplitude. Figure 1 shows representative results obtained from the emmetropic subject BW (female, 30 yr, 1.2 binocular Landolt-C acuity). The most remarkable feature of the amplitude plot in Fig.



Fig. 1. Steady-state VEP amplitude response (a), temporal phase response (b), and contrast sensitivity function (c) for subject BW. Stimuli for the SSVEP were sine wave gratings of 40% contrast, sinusoidally modulated at 8 Hz (16 rps). The 16-Hz spectral component is shown in (a) and (b). Each data point represents a 12-s net recording time (corresponding to ninety-six stimulation periods on a CAT). As an estimate of noise, an amplitude value obtained with closed eyes is shown in the left corner of (a); the corresponding phase result is meaningless and, therefore, omitted. The contrast sensitivity as shown in (c), defined as the negative logarithm of the contrast threshold, was obtained by the psychophysical method of adjustment. Stationary sine wave gratings were used as stimuli for the latter type of experiment.

1(a) is the existence of an intermediate sharp notch at medium spatial frequencies (2.5-4 cpd), where the contrast sensitivity is optimal [Fig. 1(c)]. The phase results are plotted with the phase angle being a function of spatial frequency [Fig. 1(b)]. These data are discussed in more detail below, but it may be noted that the phase function shows a change in slope in the same range of spatial frequencies where the notch in the amplitude plot occurs.

The notch in the amplitude response is a finding which is not peculiar to subject BW. This is obvious from Fig. 2 summarizing the results obtained for our fifteen subjects at 40% stimulus contrast. Although the response pattern varies widely between subjects, a pronounced loss of amplitude occurs at intermediate spatial frequencies in most cases. Despite the large

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variability of the VEP response between subjects, the location of the peaks and the trough is quite stable. The geometric mean of the notch is at 3.2 cpd with a standard error of 0.3 cpd (0.13 octave), and its half-amplitude width (relative to the mean of the two peak amplitudes) is less than an octave (factor 1.7 = 0.77 octave). The mean of the low-frequency peak is at 1.6 cpd with a standard error of 0.18 cpd (0.15 octave); the mean of the high-frequency peak is at 7.2 cpd with a standard error of 0.75 cpd (0.14 octave).

We ought to emphasize that the data in Fig. 2 have been obtained from an unbiased control group. That is, we present a complete set of data that were collected by using a randomly selected group of female subjects, with no data being discarded for whatever reason. Hence the variation in response shape between subjects is of interest in itself. Many subjects display two high peaks of VEP amplitude with a sharp notch between (CS, AL, CP, MK, AS, AF, BW, AM, RV, GM). For some subjects one of the peaks is small or even absent (EM, MB, EH, JL), and one subject shows no response at all for the given parameter settings (UZ). In this context it is interesting to note the view of Dustman *et al.*⁴⁰ that the transient VEP waveform is largely determined by hereditary factors. The variability between subjects, however, should not lead to the conclusion that amplitude results are unreliable.

Results for a given subject are remarkably reproducible even after long periods of time. Figure 3 shows an example for subject BW, where the amplitude response has been repeatedly examined over a period of 3 vr. Over this period, the shape of the amplitude plot remained relatively unchanged; a small shift of the amplitude function along the spatial frequency axis could be attributed to some variability in the viewing distance since we used no chin rest for the subjects. Yet there have been occasions where a different response pattern has been obtained [Figs. 3(f) and (h)]. During such sessions the measurement has been repeated several times, and the same altered shape has consistently been obtained. In the session in July 1986 [Fig. 3(h)], for example, we found exceptionally high-amplitude values up to $10 \,\mu V$. We have, as yet, no explanation for this irregularity.

Although amplitude data display a remarkable longterm stability, there is often more variability within one recording session with amplitudes generally decreasing in the course of the session. Despite this, the shape of the curve is basically unchanged. The length of the resting periods between several units of measurements is one factor of influence. Figure 4 shows an example of the variability of the SSVEP as obtained from subject RV during the same experimental session with unchanged stimulus parameters.

B. Three-Dimensional Plots: VEP Amplitude vs Contrast and Spatial Frequency

The double-peaked amplitude plots obtained for most subjects are not only at conflict with many previously reported results but at first sight seem at vari-



Fig. 2. Amplitude and phase response for an unbiased group of fifteen female adult subjects with normal vision. Stimulus conditions and scaling of axes as in Fig. 1.



Fig. 3. Long-term variability of the SSVEP response. Amplitude responses are shown for one subject (BW) as obtained over a period of 3 yr. Stimulus conditions as in Fig. 1.

ance with Campbell and Maffei's⁸ finding of a relationship between the (unimodal) psychophysical contrast sensitivity function and VEP amplitude data. This has led us to investigate how the shape of the amplitude plot is altered by lowering the grating stimulus contrast. Figure 5 shows representative results from one subject (BW). Amplitude is plotted as a surface over a plane spanned by spatial frequency and contrast. As can be seen, amplitude generally decreases with decreasing contrast, but the general shape of the



Fig. 4. Variability of the SSVEP response during experimental session. Amplitude and phase responses are shown for one subject (RV) as repeatedly recorded during one session on May 1984.



Fig. 5. VEP amplitude as a function of spatial frequency and contrast for one subject (BW).

amplitude vs spatial frequency plot remains unchanged for this subject.

Further measurements have been performed on a subgroup of ten subjects as not all subjects from the previous set were available for this part of the study. Figure 6 shows the corresponding results. It cannot always be decided whether a double-peaked amplitude plot remains unchanged at lower stimulus contrast, since the SNR generally also decreases with decreasing contrast, and some subjects have low responses for high contrast to begin with. It is, however, clear that a double-peaked response is not peculiar to a certain contrast level and can also be observed at lower contrast levels.

By replotting the data from Fig. 6, we can examine how VEP amplitude depends on stimulus contrast. Response can be classified into one of three categories as shown in Fig. 7. Figures 7(a) and 7(b) show data from subject AS displaying a linear relationship with log contrast over a large range of contrast and spatial frequency values. As mentioned above, such a kind of response has been reported in the literature. At the upper and lower end of the spatial frequency range there are not enough data points to determine reliably a regression line. The corresponding lines have, therefore, simply been drawn parallel to the neighboring more reliable lines. The responses have been plotted in two groups, for low and high spatial frequency, respectively, thus displaying different slopes for the respective regions of spatial frequency. That is, the slope of the amplitude vs contrast response curve is independent of spatial frequency within certain response groups, but it is not independent of spatial frequency in general. The spatial frequency value separating these two groups corresponds to the notch in Fig. 2 subject AS.

Figure 7(c) shows data from the same subject for an intermediate range of spatial frequencies. At this condition, the VEP amplitude displays a linear relationship with log contrast provided the contrast is lower than, say, 10%. At higher contrast levels, the increase on VEP amplitude is smaller. The contrast value, where this decrease of slope occurs, depends on spatial

frequency. Such a flattening has been observed in many studies and is usually being attributed to saturation. It should be noted, however, that the amplitude does not remain at a constant value at higher contrast levels but rather increases at a reduced gain.

A third type of response is shown in Fig. 7(d). At lower contrast levels, amplitude shows the familiar loglinear increase, then drops to noise level, and finally increases again. This type of response is typically found at those spatial frequency values where the notch in the spatial frequency characteristic occurs (see Figs. 1 and 2). It is obvious that the assumption of a saturation of the EP response is not sufficient to explain this sort of nonlinear behavior. It rather suggests the existence of an additional mechanism interfering with the EP generation above a certain contrast level.

Finally, it should be mentioned that the data shown in Fig. 7 do not stem from sweeps over the contrast variable but are collected from several sweeps over the spatial frequency variable (as in Fig. 1). As a result of this there was a comparatively long time delay between the recording of individual data points. Hence it might be argued that peculiarities in the contrast characteristic are artifacts of this procedure. We have excluded this probability by conducting direct contrast sweeps with the same subjects.

C. VEP Amplitude Thresholds and Contrast Sensitivity

For investigating the correspondence between grating contrast sensitivity and VEP data we employed the regression technique of Keidel and Spreng⁹ and Campbell and Maffei⁸ on the data shown in Fig. 5. Regression lines have been calculated for the log-linear part of the contrast characteristic (as shown in Fig. 7) using the low-contrast part in the case of the type three characteristic as in Fig. 7(d). Parallel lines have been fitted in such cases where not enough data points were available above noise level. The intersection of the regression lines with the contrast axis, i.e., the points of vanishing VEP response $(0 \mu V)$, have then been determined. Note that the intersection with the level of 0 μ V, and not the intersection with the noise level, is relevant since at noise level there may still be a signal present, which is just not discernible from noise.

The resulting objective contrast sensitivity functions (VEP in the graphs) for four subjects are shown in Fig. 8 together with psychophysical contrast sensitivity functions (CSF) obtained in the same subjects. We may note that both objective and subjective contrast sensitivity functions have an inverted U shape peaking at about similar spatial frequency. As the deviations between the two types of function are concerned it is difficult to decide whether they are significant. On the one hand, we have used stationary gratings for measuring the (subjective) CSF (see Sec. II). On the other hand, the VEP data have not been collected with optimum reliability of threshold determination in mind. They stem from sweeps over the spatial frequency variable, and the reliability could be improved by using direct contrast sweeps and other means.



1.0 2.0 4.0 6.0 Spat. Freq. [cpd]







16. 5.5 (01

Fig. 6. VEP amplitude as a function of spatial frequency and contrast for ten subjects.



Fig. 7. VEP amplitude data from Fig. 6 for subject AS replotted as a function of contrast: (a) and (b) log-linear characteristics; (c) gain reduction for three different values of spatial frequency; (d) type three characteristics (for details see text) for three spatial frequencies, where amplitude decreases for contrast values between 5 and 20%.

In Fig. 6, the objective contrast sensitivity function (OCSF) can be imagined as a horizontal path at the foot of the VEP mountains. For all subjects this line has the inverted U shape of a CSF in being unimodal with a maximum at medium spatial frequency.

IV. Discussion of Amplitude Results

A. Amplitude vs Spatial Frequency

Our findings concerning the SSVEP amplitude, as shown in Figs. 1 and 2, confirm what has previously been reported by Tyler and co-workers^{25–29}; the VEP response normally shows a pronounced minimum for spatial frequencies of ~3 cpd, a condition for which the subjects' CSF is maximal. The problem is not removed by taking notice of the fact that the stimuli used for eliciting the VEP response were displayed at suprathreshold contrast values. All our subjects perceived the stimulus contrast generally in direct proportion to the photometric contrast, as has been reported by Georgeson and Sullivan⁴³ and Cannon.⁴⁴ This implies that the SSVEP amplitude bears no obvious relationship to the perception of suprathreshold grating contrast.

Thus we are left with the question of whether the VEP amplitude could serve as a direct measure of visual contrast sensitivity (i.e., without a regression procedure) as has been claimed by many researchers (see Refs. 20, 21, 23, 35, 36, and 45-54). This "wellestablished" (Ref. 23, p. 1481) view was first challenged by reports from Tyler *et al.*²⁵ reporting a notch in their amplitude functions around 1-4 cpd. Harter et al.²⁴ have reported bimodal amplitude functions along with unimodal ones for small infants. Interestingly, Harter's results of bimodal response functions have been neglected in a review by Dobson and Teller,⁵ which also covered Harter's work. Recording from the cortical surface of the alert monkey, Nakayama and Mackeben⁵⁵ have obtained narrowband amplitude functions, which are equally dissimilar from a CSF.

What accounts for the contradicting results? Tyler (personal communication) assumed that the very high stimulus contrast (80%) used in their studies (e.g., Tyler *et al.*²⁵) might explain some of the differences. Since our results were obtained with contrast values of at most 40%, this cannot be sufficient. Other sources to consider are differences in experimental conditions



Fig. 8. Contrast sensitivity function and objective contrast sensitivity function (here indexed by VEP) as assessed by the VEP regression technique for four subjects. The additional traces (HC) for subjects BW and MB show the result of applying the regression technique to the high-contrast part of type three characteristics as shown in Fig. 7(d).

such as electrode positioning, the use of sine-wave gratings vs checkerboard patterns, the use of phase reversal vs on/off-type modulation, temporal frequency, etc. To illustrate this issue, the various experimental conditions are summarized in Tables I and II. From this it is apparent that no single experimental difference can be made liable. For example, most of the earlier studies use checkerboard patterns for stimulation. One might argue that the VEP response to these stimuli could be thought of a superposition of responses to sine-wave components in a 2-D Fourier analysis of the checkerboard stimuli, thus masking a possible notch in the amplitude response. Unimodal amplitude functions have, however, also been reported with sine-wave stimulation, and, conversely, bimodal functions have been found with checkerboard stimulation.²⁴ Explanations based on the type of temporal modulation, the temporal frequency, or the differences in electrode positions face similar problems.

A simpler explanation would apply to at least eight of the thirteen studies summarized in Table I: The range of spatial frequencies (in case of checkerboard stimulation the fundamental spatial frequency component, i.e., the inverse of the check diagonal) has been restricted to relatively low values, not exceeding 7 cpd. The resulting VEP plots may, therefore, simply consist of the low-frequency components of bimodal response functions. Indeed Parker and Salzen⁵⁶ by recording up to 23 cpd obtained a pronounced decay at 6–8 cpd, not too different from our results.

For the remaining four studies (Levi and Harwerth,³⁶ Pirchio *et al.*,²⁰ Regan,⁵¹ Rentschler and Spinelli⁵²) we can only guess that data have been selected with a bias on unimodal amplitude functions. In case a sweep technique is not available it might be difficult to avoid such a selection of data, since recordings over a wide range of spatial frequencies can only be made by collecting data during several experimental sessions. It would not seem unlikely that unexpected results are then discarded as artifacts. Not entirely incompatible with this possibility is the fact that many of the studies listed in Table I are based on only one or two subjects.

B. Amplitude vs Contrast

Concerning the influence of stimulus contrast on VEP amplitude, our results of a linear relationship with log contrast, as shown in Figs. 7(a) and (b), correspond well to what has widely been reported in the literature.^{8,15,22,25,36,57,58} Some of these studies note that more than a single regression line will often be needed to fit the data. Campbell and Maffei⁸ found that two straight lines are required below 3 cpd. Similarly, Apkarian et al. (Ref. 28, Fig. 6) found two lines necessary. Nakayama and Mackeben⁵⁵ showed that for fitting steady-state VEP data of the alert monkey, two lines are almost always required. However, unlike in our results illustrated in Fig. 7(c) in these three studies the slope of the regression line is higher in the upper contrast range than in the lower range. Yet these results are not directly comparable, since the kink occurs at very different contrast values. In Campbell and Maffei's⁸ data it occurs at a contrast as low as 1.6% and in Apkarian et al.'s²⁸ data at 50 and 70%. Both these values lie outside the range of contrast which we surveyed. Nakayama and Mackeben⁵⁵ present detailed statistical data on their critical contrast values; they lie between 10 and 15% contrast. In this case the different topology of the monkey's visual

| Authors | Relevant fig. | Ss 7 s | `ranslent/ teady -s. | Spatial modul. | Temporal modul. | Mod. freq. (rps)1 | On/off vs. phase-rev. | Contrast (%) | Screen luminance (cd/m ²) | Vlewing angle (deg) | Sp.freg. range ² (cpd) | Electr. pos. ³ |
|--------------------------------|------------------|-----------------------|---------------------------------------|-------------------|--------------------|-------------------------|-----------------------------|------------------|---|----------------------------|---|------------------------------|
| Armington et al. 1971 | 7 | 2 adults | SS | Sine & chkb | Square | 2 | ph-rev | 96 | 100 td | 17 | 0.2-4 | e |
| Regan & Richards 1973 | 1 | 1-4 adult | s T | Checkerboard | Square | 3 | ph-rev | 4, 15 | 21 | 2 | 0.7-7 | d |
| Parker & Salzen 1977b | 5&6 | 6 adults | т | Sinewave grt | Square | 320 msec | on/off | & 100 87 & 50 | 6 & 2 | 6 | 0.5-23 | b |
| Regan 1977c ⁴ | 1 | 1 amblyop | еT | Checkerboard | Square | ? | ph-rev | ? | ? | ? | 0.3-2.6 | f |
| Levi & Harwerth 1978 | 2&4 | 5 amblyop | oes SS | Sinewave grt | Square | 16 Hz | on/off | 44 | 15 | 7 | 0.5-16 | Ь |
| Jones & Keck 1978 ⁵ | - | 2 adults | Т | Sinewave grt | Square | 20 msec | on/off | below 40 | 10 | 10 x 6 | - | j |
| Pirchio et al. 1978 | 2 | 1 adult | SS | Sinewave grt | Square | 16 | ph-rev | 30 - 50 | 7 | 7.3 - 25 | 1.5-20 | f |
| Florentinl et al. 1980 | 1 | 3 infants 1 adult | SS | Sinewave grt | Square | 16 | ph-rev | 20 - 50 | 0.06 & 6 | 25 x 20 & | 0.5-6 | f |
| Groneberg 1980 | 1&6 | 5 infants 7 adults | SS | Checkerboard | Square | 14 | ph-rev | 100 | 24 | 12.5×10 5 - 16 | 0.5-3 | с |
| Fiorentini et al. 1983 | 6 | 2 infants | SS | hor. sinewv. | Square | 14 | ph-rev | 30 | 6 | 28 | 0.15-2 | f |
| Regan 1983 | 1&2a | 2 adults | SS | Sinewave grt | Sine | 8 & 17 | ph-rev | 25 & 50 | 103 | 35 x 22 | 0.3-30 | h |
| Rentschler & Spinelli 83 | 3 1 | 1 adult | SS | Sinewave grt | Square | 16 | ph-rev | 40 | 6 | 4 | 2 - 30 | i |
| Sokol et al. 1983 | 2-4 | 2 adults | SS | Checkerboard | Square | 7 & 15 | ph-rev | 30 & 85 | 78 | 15 x 19 | 0.09-2.8 | а |
| Padmos et al. 1973 | 7a | 5 monkey | s T | Checkerboard | Square | 15 msec | on/off | 25 - 100 | 20 | 12 | 0.1-5 | k |

Table I. Experimental Conditions for Reported Unimodal Amplitude/Spatial-Frequency Plots

¹For transient stimulation the stimulus presentation time is given; for steady-state on/off stimulation the frequency in Hz is stated.

²For checkerboard stimulation the corresponding fundamentals's spatial frequency is given. When both adults and infants are examined, the ranges for adults are given.

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<sup>3</sup>Electrode positions:

a) 1 cm above inion & ear

b) 2 cm above inion & ear

c) 3 cm above inion & ear

d) 1 cm above inion & left mastold
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e) 2.5 cm above inion & right mastold
f) 2 cm above inion & vertex
g) inion & 7 cm anterior
h) inion & 9 cm anterior

i) 2 cm above inion & 2 cm lat. left
j) 3.7 cm above inion & 3.7 cm lat. left
k) T6 & mid-frontal

 $4_{n?n} = not reported$

⁵No figure, shape of SFC mentioned in text only (p. 656).

| Authors | Relevant fig. | Ss 5 | Franslent/ steady-s. | Spatlal modul. | Tempora modul. | l Mod. freq. (rps)1 | On/off vs. phase-rev. | Contrast (%) | Screen luminance (cd/m ²) | Vlewing angle (deg) | Sp.freg. range ² (cpd) | Ele pos |
|-----------------------|------------------|------------------------|-------------------------|--------------------------------|-------------------|---------------------------|-----------------------------|-----------------|---|---------------------------|---|------------|
| Harter et al. 1977 | 17.5 | 10 infants | T. | Checkerboard | Square | 10 usec | on/off | 100 (?) | flash-EP | 22 | 0.12-1.9 | ε |
| Tyler et al. 1978 | 4-10 | 4 adults | SS | Sinewave grt(?) | Square | 10 - 50 | ph-rev | 90 (?) | 0.4 - 13 | 10 x 12 | 0.2-20 | 18 |
| Tyler et al. 1979 | 2-9 | 2 adults | SS | Shewave grt & | Square | 24 | ph-rev | 80 - 90 | 46 & 360 | 2 - 20x15 | 0.2-30 | 1 |
| Apkarian et al. 1981 | div. | 3 patlents 6 adults | SS | Squarewave grt Sinewave grt | Square | 28 & 30 | ph-rev | 68 - 80 | 46 | 7x6-20x15 | 0.2-20 | I |
| Tyler et al. 1984 | 2 | l adult | SS | Sinewave g. (?) | Square(?) | 24 & 45 | ph-rev | 80 ? | 46 (?) | 2 - 20x15 | 0.3-20 | 18 |
| Norcia & Tyler 1985 | 1&2 | 215! infant | is SS | Sinewave grt | Square | 12 | ph-rev | 80 | 80 | 6 - 26 | 2 - 20 | I |
| Tyler & Apkarian 1985 | 2-6 | 2 adults | SS | Slnewave grt | Square | 16 - 48 | ph-rev | 65 - 80 | 40 | 10 x 12 | 0.15-20 | I |
| This report | 1-6 | 15 adults | SS | Sinewave grt | Sine | 16 | ph-rev | 40 | 8 & 17 | 5 | 0.5-25 | (|
| Nakayama & Mackeben 8 | 2 div. | 2 monkeys | SS | Sinewave grt | Sine | 8.8 - 48 | ph-rev | 18 - 45 | 20 | 7.3 x 5.3 | 0.3-20 | |
| 1 | | | | | | | | | | | | |

Table II. Experimental Conditions for Reported Multimodal Amplitude/Spatial-Frequency Plots

For transient stimulation the stimulus presentation time is given.

²For checkerboard stimulation the corresponding fundamentals's spatial frequency is given. When both adults and infants are examined, the ranges for adults are given.

³Electrode positions: Like in Table 1, plus 1) 3 cm above inion + 3 cm lateral right m) 3 cm above inion + 3 cm further above 1) 10 cm above inion + 3 cm further above n) 1 cm above inion + 3 cm lateral right o) 2 cm above inton + 2/3 Inton/naston p) Cortex surface (!)

15 March 1988 / Vol. 27, No. 6 / APPLIED OPTICS 1081 cortex and the technique of recording directly at the surface of the cortex might account for the differences.

As the earlier claim of Campbell and Maffei⁸ is concerned, it is clear that our data do not support the proposition that the slope of the linear regression between VEP amplitude and log contrast is independent of spatial frequency. Within one subject, we find ranges of spatial frequency where this is the case, but generally slopes differ between such ranges.

There is also general agreement that response saturation often occurs above a certain contrast level. The onset of saturation has been found to depend on stimulus luminance^{59,60} and spatial frequency (observable from Kulikowski's⁵⁸ data). Although it is mostly assumed that saturation occurs above 10–30%, Apkarian *et al.*'s²⁸ data show that saturation can be absent up to contrast values of 80%.

Our results as shown in Figs. 7(a)-(c) correspond to these general findings. In our data, gain reduction (saturation) is most prominent for medium spatial frequencies. Indeed, many of the amplitude surfaces of Figs. 5 and 6 would be consistent with the assumption that the onset of gain reduction is for intermediate spatial frequencies at lower contrast levels than is the case for lower and higher spatial frequencies. Note that, different from this, Nakayama and Mackeben's⁵⁵ double-peaked amplitude surfaces for the monkey can be described as a linear contrast dependency for medium spatial frequency and gain increase for low and high spatial frequencies.

We feel, however, that the generality of a linear relationship between VEP amplitude and log contrast has been overrated in the past since relevant results have been obtained only at a few selected stimulus conditions. For example, Campbell and Kulikowski's¹⁵ claim concerning a log-linear interrelation over a wide range of contrast values is based on data from one subject obtained at just one spatial frequency value. Only recently²⁹ [Tyler and Apkarian (1985)], a response of the type shown in Fig. 7(d) has been reported. A less pronounced decay of VEP response with increasing contrast had been reported by Apkarian et $al.^{28}$ Yet this sort of behavior, for which the authors coined the term oversaturation, only occurred at very high levels of contrast (above 80%, Tyler, Smith-Kettlewell Inst.; personal communication).

C. Underlying Neural Mechanisms

To evaluate the implications of our findings for the attempt to assess visual function by analyzing SSVEP amplitude, it is useful to consider the conditions that are sufficient for predicting psychophysical grating detection thresholds from amplitude data obtained at suprathreshold constant contrast values:

linear increase with log contrast for all spatial frequencies up to a certain contrast level;

slope independent of spatial frequency;

absence of saturation or change of gain within this contrast range.

Figure 9 illustrates a hypothetical VEP amplitude distribution that meets these requirements. It is obvi-



Fig. 9. Hypothetical VEP amplitude surface which meets the requirements commonly assumed when contrast sensitivity is estimated from suprathreshold amplitude responses obtained at constant contrast. Note that our data are not consistent with such a model as can be seen from Fig. 6.

ous that our data, as shown in Fig. 6, are incompatible with these conditions.

We may now ask the question as to the neuronal basis of the peculiarities in the amplitude response. Regarding the bimodality of the amplitude response function, some considerations have been reported in the literature. Harter et al. (Ref. 24, p. 352) assume two mechanisms related to cortical and subcortical processing. They base their conjecture on differences found between measures of infant acuity when assessed through optokinetic nystagmus (ON) methods as opposed to assessment by preferential looking (PL) techniques. They assume ON as related to subcortical and PL as related to cortical processing. Regan⁶¹ hypothesized that VEP latency differences between the upper and lower hemiretinae, as found by Jeffreys and Axford,⁶² may account for a signal cancellation at the electrode location for certain stimulus parameters. This explanation is not consistent with the results of exploratory experiments where we obtained bimodal amplitude functions with half-field stimulation. Another explanation might be an interaction or electrical cancellation of responses originating from different cone systems. Indeed, Spekreijse et al.,60 using the cone-specific stimulation technique as developed by Estevez and Spekreijse,⁶³ report different optimum spatial frequencies for transient VEPs from the three cone systems and also show that saturation disappeared when they used the cone-specific technique.

The common ground of such explanations is the assumption of several, simultaneously stimulated, neuronal subsystems differing in their spatio-temporal characteristics. Such mechanisms can also be postulated for different contrast ranges. The amplitude vs contrast function could then be thought of as being brought about by a mechanism with a log-linear characteristic operating in the lower contrast (LC) range, and the gain reduction or indeed a decrease in response for high contrast could be attributed to the superposition of a second mechanism, stimulated at higher contrast (HC) values, and operating in opposite temporal phase thus leading to signal cancellation. The existence of such two mechanisms could account for the fact that the gain increases for high contrast in the monkey and could also serve to explain the bimodality

of the amplitude function provided the following (sufficient) requirements were met:

(a) LC reacts over the entire range of contrast values; HC reacts for higher contrast values only (above say 5%).

(b) The temporal phase lags of LC and HC depend differently on spatial frequency. For medium spatial frequency LC and HC tend to be in opposite phase leading to signal cancellation at higher contrast.

(c) The onset threshold of LC corresponds to the psychophysical contrast threshold but not so for HC. (We have tentatively drawn regression lines through the high-contrast part of our type three responses: they bear no relationship with psychophysical contrast sensitivity whatsoever.)

We list these properties as a set of constraints on future models. Whether they directly reflect what is known from neurophysiological research is difficult to say. It should be noted, however, that Kaplan and Shapley⁶⁴ distinguished two groups of cells in the monkey's geniculate body (magnocellular X cells and parvocellular X cells) differing in their respective contrast sensitivities. The projections of such cell groups to the visual cortex might be related to the properties of the VEP amplitude response at issue.

V. Results: Phase Data

Results concerning VEP temporal phase have already been shown in the previous section along with the amplitude data in Figs. 1 and 2. From these plots it is apparent that phase data also vary considerably between subjects. Nevertheless, the following observations can be made:

First, phase angles generally increase with increasing stimulus spatial frequency. The dependency tends to be smooth in the ranges of relatively low and high spatial frequency, whereas a discontinuity is often found at intermediate spatial frequencies. Most noteworthy, this discontinuity is located at the same spatial frequencies where the notch in the amplitude plot occurs. The VEP phase plots can reasonably well be approximated by two straight lines, one with a smaller slope $(0-45^{\circ}/\text{octave})$ for the low spatial frequency range and one with a greater slope $(90-135^{\circ}/\text{octave})$ for the high spatial frequency range (see Fig. 10).

Second, the discontinuity at medium spatial frequency shows itself in Fig. 2 either as a sudden steep increase in phase or as a pronounced decrease (RV, EM, but see below). In other cases it is absent. It seems as if the phase plot is composed of two independent parts which either fit together at medium spatial frequency or do not fit together.

Third, to assess the reliability of phase results we have calculated standard errors of the mean phases, which are shown for some subjects in Fig. 2. As can be seen, phase results are remarkably reliable and are often even reliable when amplitudes are very low. It follows that the VEP phase can serve as an indicator of whether a certain amplitude/phase pair can be considered to be above noise level.

Figure 10 shows VEP phase results as a 2-D function



BW

AS

Fig. 10. Temporal phase of the SSVEP as a function of spatial frequency and contrast for four subjects (AS, BW, RV, MB). Absolute phase values have been assigned so that distances are minimized for both independent variables (for details see text). Note that the axes are rotated relative to Figs. 5 and 6.

of both stimulus contrast and spatial frequency. For each of the four subjects (AS, BW, RV, MB) the full set of data has been obtained in a single session to increase reliability. Possible effects of the sequence of stimulation have been compensated for by varying both the contrast and spatial frequency parameters in increasing and decreasing order. It should be clear that phase values were always obtained together with amplitude values as the result of the Fourier transform of the VEP response. Note also that the contrast and spatial frequency axes have here been scaled so that the latter increases to the left and contrast increases toward the observer. The obvious reason is that higher phase values would otherwise hide lower phase values.

For increasing contrast, phase values generally decrease, with the exception of two subjects: BW and MB show a small increase of $\sim 50^{\circ}$ at high contrast values. The slope of the phase angle to contrast interrelation changes between 5 and 15% contrast and tends to be smaller in the region of high contrast. There is also a difference in the slope of the phase-angle/spatial-frequency interrelation as the ranges of high and low spatial frequency are concerned. The latter difference is more pronounced at low values of contrast. It is interesting to note that the individual contrast Table III. Phase vs Contrast

| Sj | critical contrast f. phase | critical contrast f. ampl. | notch (cpd) from to | phase increase LC, LSF | phase increase LC, HSF | phase increase HC, LSF | phase increase HC, HSF |
|----|----------------------------------|----------------------------------|---------------------------|------------------------------------|------------------------------------|------------------------------|-----------------------------------|
| AS | 5% | 5-10% | 3.2 | +160° | +100° | -50 ⁰ | -50 ⁰ |
| BW | 10% | 5-10% | 2.2 5.0 | or -200° -50° | -200° | +50 ⁰ | +50 ⁰ |
| MB | 15% | 5-15% | 1.5 2.2 | -150 ⁰ | -100 ⁰ | +50 ⁰ | +50 ⁰ 100 ⁰ |
| RV | 10-15% | 10-15% | 2.2 3.2 | -150 ⁰ 250 ⁰ | -125 ⁰ 225 ⁰ | -125 ⁰ | -25 ⁰ 125 ⁰ |
| | | | | | | | |

"critical contrast for phase": contrast value where slope of phase changes

"critical contrast for amplitude ": contrast value where slope of amplitude changes

"notch": Notch of the amplitude vs. spatial frequency plot (SFC), cf. Figs. 1 & 2.

LC: Low contrast range (up to critical contrast for phase)

HC: High contrast range (above critical contrast for phase)

LSF: Low spatial frequency range (up to notch)

HSF: High spatial frequency range (above notch)

value (critical contrast), where the change of slope occurs, corresponds to the contrast value where the amplitude vs contrast plot displays the change in gain (see Fig. 7). Table III gives a summary of the phase results of the four subjects tested. The phase surface can be thought of as consisting of four separate planes for the four quadrants, separated by a critical contrast and spatial frequency value. These critical values, which correspond to the values where peculiarities in the amplitude response occur, are somewhat different for each subject.

As the problem of assigning an absolute value to a given phase result is concerned, we should emphasize once again that phase values are only defined modulo 360°. The problem has been discussed more thoroughly elsewhere,³⁹ but some remarks seem necessary. When more than one independent variable is available, as is the case in Fig. 9, the principle of minimum phase difference can be more rigorously applied. In some cases this may lead to a different phase assignment than in case of one variable (e.g., spatial frequency as in Fig. 2). For example, the phase discontinuity at 2 cpd for subject RV, which had been shown as a decrease in Fig. 2, is shown here in Fig. 10 as an increase. In Fig. 10 the value has been assigned with a phase difference larger than 180°, since this leads to a smoother overall surface when the relation with varying contrast is also taken into account. It might thus well be that the phase response at the discontinuity can generally be described more parsimoniously as a phase increase when more variables are taken into account.

The question of whether VEP temporal phase has a perceptual correlate has been addressed in an exploratory experiment. In much the same way as has been suggested earlier for the latency of the neuromagnetic

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response by Williamson et al.,65 Rentschler and Spinelli^{52,66} considered the possibility that the temporal phase lag of the SSVEP might reflect some internal sensory encoding process which is critically dependent on stimulus spatial frequency. Thus they compared the phase values of one subject to her psychophysical reaction times to the onset of sinusoidal gratings. Figure 11 shows comparable data for two of our subjects, namely, BW and RV. These subjects have been selected for their pronounced phase discontinuity to establish whether these individual characteristics are also reflected in their reaction time behavior. This was not the case. Besides the phase values of the SSVEP and reaction times, the graph shows earlier psychophysical data reported by Breitmeyer.⁶⁷ Both psychophysical and electrophysiological data show the same tendency, namely, an increase of phase lag, or reaction time, with increasing spatial frequency. The phase data, however, are different in that (after appropriate scaling) they lack the steep increase at higher spatial frequencies, which is typically found in reaction time experiments.

VI. Discussion of Phase Results

Little attention has been paid in the past to analysis of the temporal phase lag of the steady-state VEP. Of special hindrance was the fact that no criteria as to the reliability of phase values had been developed before. We attempted to resolve this problem,³⁹ and from our results two conclusions are warranted: First, the analysis of temporal phase properties of the SSVEP is of paramount importance for assessing the reliability of VEP results in general. Phase results are important also for enabling one to conduct phase-locked analysis. Third, VEP phase data also seem to have some signifi-



Fig. 11. Reaction time to the onset of sine wave grating stimuli with 40% contrast and phase results replotted from Fig. 2 for two subjects (BW, RV). Phase results have been rescaled accordingly based on their temporal frequency of 16 Hz. Reaction time results from Breitmeyer⁶⁷ are included for comparison.

cance as an indicator of the sensory encoding process, although more definitive evidence of this is required. We shall now try to elaborate these conclusions:

Our finding of a general increase of temporal phase lag with increasing spatial frequency is in line with the findings of Rentschler and Spinelli^{52,66} and Lorbeer,⁶⁸ with Nakayama and Mackeben's⁵⁵ data for the monkey, and with reports on the increase of the latency of transient VEP.^{28,56,58,69-72} There is no report on any peculiarities for medium spatial frequency in these studies. This is probably due to the fact that most of these studies were restricted to low spatial frequencies anyway (see Table I).

As to the question of how the temporal phase depends on stimulus contrast, no data have been reported as yet. By referring to the results obtained by Shapley and Victor⁷³ for the cat, Nelson *et al.* (Ref. 74, p. 424) conjecture that phase is rather independent of contrast. Under the assumption of constant phase they advocate the use of phase-locked VEP analysis, which will improve the amplitude SNR compared with more conventional rms-amplitude determination. From our data, we cannot support the claim of an independence of phase on contrast. From this it fol-

lows that the application of phase-locked analysis for determining contrast thresholds by use of the regression technique (Fig. 8) when a wide contrast range is used will lead to an underestimation of contrast sensitivity (for a detailed discussion see Ref. 39). We carried this through for the data shown in Fig. 8 and found an underestimation of $\sim 10-16$ dB.

For the transient VEP, Kulikowski⁵⁸ and Musselwhite and Jeffreys⁷⁵ obtain a decrease in latency for increasing contrast. The latency decreases in the Musselwhite and Jeffreys study amount to 35 ms for an increase of contrast from 4 to 100%. (The stimulus duration was 150 ms.) These results are in line with those of the present study.

As the functional significance of VEP phase data is concerned, we may note that Breitmeyer,⁶⁷ Lupp *et* $al.,^{76}$ and Lupp⁷⁷ found an increase in reaction time to the onset of sinusoidal gratings with increasing spatial frequency. Data on the increase of VEP phase or latency with increasing spatial frequency are available from Rentschler and Spinelli,⁶⁶ and Parker and Salzen,⁷¹ respectively, whereas Williamson *et al.*⁶⁵ measured the phase lag of the electromagnetic response. Table IV shows that our results are consistent with these data.

Thus it appears that the general tendency of phase and reaction time data for increasing spatial frequency is the same. From our data, this is also true for variations of stimulus contrast. The increase in phase (and latency) for spatial frequency variation is, however, much smaller than that for reaction time and amounts to \sim 50% of the latter. Individual characteristics of the phase response also do not seem to be reflected in reaction time as is apparent from Fig. 11. Reaction time data might thus be thought of as composed of

Table IV. Reaction Time and Temporal Phase

| Reaction time: Author or Sj | Spat.freq. range (cpd) | RT increase (ms) | | |
|--------------------------------|------------------------------|------------------------|--|--|
| Breitmeyer (1975) | 1 - 10 | 110 | | |
| Lupp et al.(1976) | 1 - 10 | 60 | | |
| RV | 1 - 10 | 65 | | |
| BW | 1 - 10 | 65 | | |

| Phase: | Spat.freq. range (cpd) | Phase increase | Equivalent latency increase (msec) |
|--------------------|------------------------------|-------------------|---|
| Williamson et al. | 1 - 10 | - | 50 |
| Rentschler & Spin. | 1 - 10 | 260 ⁰ | 45 |
| Parker & Salzen | 1 - 10 | - | 45 |
| RV, extrapolated | 1 - 10 | 186 ⁰ | 32 |
| BW, extrapolated | 1 - 10 | 200 ⁰ | 35 |

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several parts where only one component is captured by temporal phase results (see Ref. 78).

VII. Conclusions

The use of a digital sweep technique for variations in stimulus spatial frequency and contrast enabled us to establish that the steady-state VEP shows considerable variability between subjects but is reliable within them. Our main findings were:

(a) The amplitude and phase characteristics of the SSVEP were analyzed for an unbiased group of fifteen healthy females, thus providing control values for the comparison of clinical data.

(b) There is no general correlation between VEP amplitude and perception, but grating contrast thresholds correspond to VEP thresholds. The latter finding confirms earlier results by Campbell and Maffei.⁸

(c) The absence of a correlation between the VEP and suprathreshold contrast perception is probably due to the interaction of neural mechanisms selectively sensitive to low or higher stimulus contrast.

(d) By applying a principle of minimum phase difference it is possible to use the VEP temporal phase as an indicator of VEP data reliability.

(e) VEP phase seems to be related to perceptual encoding processes as measured by psychophysical reaction time to the grating stimulus onset.

(f) Noise indicators obtained in conditions of absent periodic stimulation are not useful for determining SNR (see Appendix).

We conclude that the steady-state VEP is a reliable means for assessing the function of the visual nervous pathway provided that a technique for the rapid acquisition of VEP data is available. The characteristics of the VEP should, however, be analyzed in their own right as their correlation to processes of spatio-temporal vision is limited.

From the many people who have contributed by helpful discussions we especially thank Manfred Mackeben, Christopher W. Tyler, Tony Norcia, and Ian Murray. We further thank Christopher Tyler for drawing our attention to the 3-D representation of the VEP amplitude data. Bernhard Treutwein has helped with the painstaking contrast calibrations, and Hans Brettel gave initial help with computer-based grating generation.

This study was supported by Fraunhofer-Gesellschaft grant InSan I-0784-V-6385 to I. Rentschler.

Appendix

In this study we determined a noise amplitude level, quite conventionally, by either having the subjects have their eyes closed or look at a white wall. Both methods give comparable results; we obtain values of the order of 1 μ V (with 12-s net recording time per stimulus, corresponding to ninety-six stimulation periods at 8 Hz). For such a procedure to be meaningful it is usually assumed that a given VEP response can be modeled as a sum of a signal and a noise level with the noise being independent of the signal. Two observations from the data presented here suggest, however, that these assumptions are not valid. First, in the contrast-variation plots of Fig. 7, the minimum amplitude values, which are found at a contrast value slightly above the extrapolated threshold, lie significantly ($p = 10^{-9}$) below noise level as determined with closed eyes. This is impossible when noise is independent from the signal. Second, at this amplitude level, which is below the conventionally determined noise level, the corresponding phase can still be reliably determined. Again this implies that noise is actually lower in the presence of a signal.

Thus it seems that background EEG activity is suppressed in the presence of even a small VEP. Such a phenomenon is not unlike the well-known alpha blockade. Hence noise levels obtained as described above are not a valid quantity for determining SNR, actual SNRs are much higher. A noise determination method as used by Tyler (personal communication) is more appropriate: In the temporal Fourier analysis, a component with a temporal frequency slightly different from the signal frequency (e.g., 15 Hz for the 16-Hz VEP component) is used as an indicator of noise. Since in a discrete Fourier analysis the frequency difference is always larger than the frequency resolution of the Fourier analysis [i.e., than 1/(net recording time)], no stimulation-correlated signal energy will be present there. On the other hand, if the frequency difference is small enough it can be assumed that a VEP response at that close-by frequency is similar in amplitude to a response at the target frequency, so that this (15-Hz) component can be truly regarded as a noise indicator, i.e., as a response in a no-stimulation condition.

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