

## **Variability of the steady-state visually evoked potential: Interindividual variance and intraindividual reproducibility of spatial frequency tuning**

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**Abstract.** At low contrast levels there is good agreement between the psychophysical contrast sensitivity function and the tuning curve of the visually evoked potential (i.e., VEP amplitude vs spatial frequency). At high contrast, however, some researchers have found bimodal VEP tuning curves whereas others have not. We studied the VEP in 22 subjects in a short-term cross-sectional study and in 13 subjects in a longitudinal study over 8 sessions covering 28 days. Grating stimuli with 60% contrast were square-wave modulated in time (7.8 reversals/s) and space (0.06–16 cycles/degree). We found large interindividual variance in the shape of the tuning curves; about half of the subjects showed a unimodal shape, while the other half showed a bimodal one (with a 'notch' between 1 and 2 cycles/degree). These features turned out to be stable in the longitudinal study, where variability could mainly be ascribed to a multiplicative influence common to all spatial frequencies. The marked interindividual differences in the shape of the tuning curve, which seem to be intraindividually stable, may explain previous discrepancies. It is not yet clear why the notch exists in about half of our subjects.

### **Introduction**

The cortical visually evoked potential (VEP) is thought to reflect neuronal processing of visual stimuli. The VEP can be easily recorded in humans. For its use as a reliable tool in research and clinical applications, its variability both within subjects over time and between subjects must be evaluated. An interesting application of the VEP is assessment of visual function by measuring the 'tuning curve', i.e., VEP amplitude vs spatial frequency. Extrapolating the high-frequency cutoff to zero amplitude is an index of visual acuity. With regard to the shape of the tuning curve when high-contrast gratings are used, however, discrepancies exist in the literature: Some groups report a unimodal curve resembling the psychophysical

contrast sensitivity function [1, 2, 3], whereas others report bimodal shapes [4, 5, 6], e.g. with a 'notch' occurring in the medium spatial frequency range.

The aims of this study were twofold. First, we wanted to examine the shape of the tuning curve in an appreciable sample size, as the 'notch' makes high-spatial-frequency extrapolation more difficult. Second, we wanted to determine the intraindividual long-term reproducibility of the shape of the tuning curve and of its absolute amplitude as well as to find out whether the 'notch' is constant within an individual. To accomplish the first aim, we performed a short-term cross-sectional study and to accomplish the second aim we did a longitudinal study.

### **Subjects and methods**

*Subjects.* Twenty-two subjects (12 women and 10 men), aged 25–68 years, participated in the cross-sectional study. Thirteen subjects (5 women and 8 men), aged 23–67 years, were examined in the longitudinal study in eight recording sessions covering 28 days. There were two sessions per week at identical time of day with alternately 3 and 4 days' interval. The only selection criterion for the subjects was normal visual acuity.

*Methods.* Subjects viewed the stimuli binocularly with undilated pupils on a video monitor with a frame rate of 73 Hz and a resolution of  $480 \times 391$  pixels. The screen subtended  $15^\circ \times 12^\circ$  of visual angle at a distance of 114 cm. Vertical gratings with a mean luminance of  $30 \text{ cd/m}^2$  and 60% contrast were square-wave modulated in time (7.8 reversals/s) and space. Spatial frequencies were presented in a counterbalanced order in 12 steps, ranging from 0.06 to 16 cycles/degree. One border between the stripes always crossed the center of the screen, thus avoiding 'subharmonics', which can occur using unbalanced stimuli at low spatial frequencies. A small cross in the center of the screen served as a fixation target. To increase their attention and control fixation and accommodation, subjects had to report a randomly chosen digit, which appeared every 5 to 10 s for 300 ms in the center of the display.

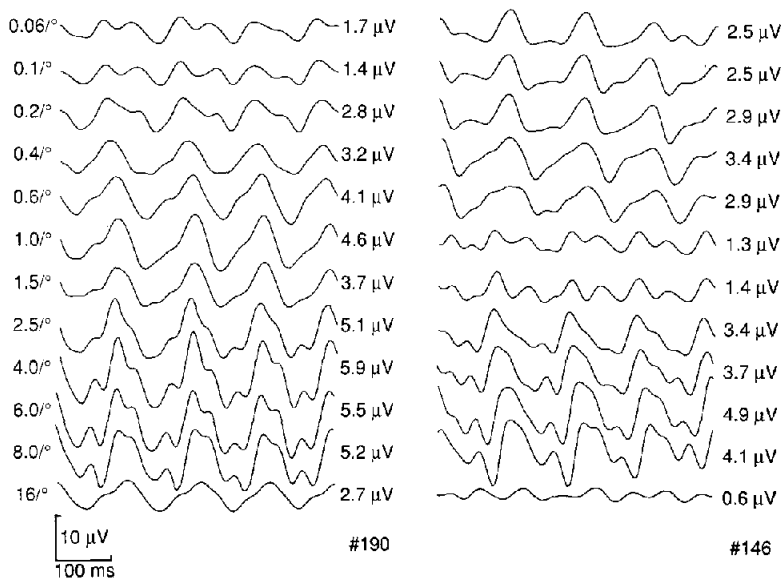
Electrode placement was Oz vs Fz [7]; the left ear was grounded. Potentials were amplified and bandpass filtered (1–70 Hz, first-order filters) using a standard electroencephalographic machine (Toennies). Signals were digitized to a resolution of 10 bits at a sampling rate of 500 Hz and recorded by a small computer (Z80), which also generated the stimuli. Sixty sweeps of 512 ms-duration were averaged and continuously displayed. A sweep was rejected whenever the signal exceeded  $\pm 100 \mu\text{V}$ . The reversal frequency was

adjusted to yield an integer number of reversals per sweep, thus eliminating 'spillover' effects in Fourier analysis. VEP amplitude was measured in the frequency domain as the amplitude at the stimulation rate.

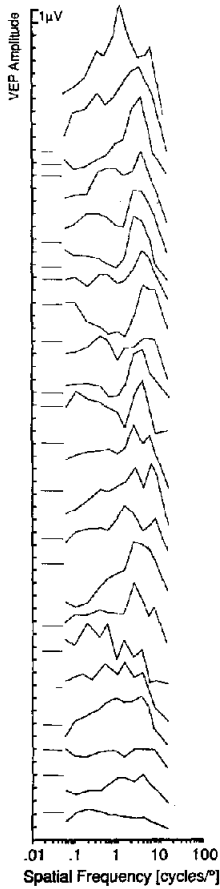
At the beginning of each session, a 'clinical routine VEP' was obtained using a transient checkerboard (0.4° check size, 1.5 reversals/s), as this gives a very reliable response and a clear-cut latency measure. All stimulus conditions were repeated four times.

## Results

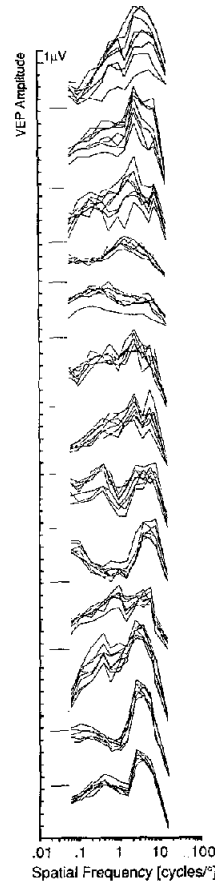
Figure 1 presents original VEP recordings from two subjects. Spatial frequency increases from top to bottom. The values in microvolts represent the spectral amplitude at 7.8 Hz (corresponding to four peaks per sweep). One subject (left panel of figure) showed a unimodal tuning curve; amplitude increases monotonically from low spatial frequencies to a peak at 6 cycles/degree and declines at higher spatial frequencies. The other subject (right panel) showed a bimodal tuning curve with a minimum of the 7.8 Hz



*Fig. 1.* Original VEP recordings from two subjects (left and right panel). Spatial frequency increases from top to bottom and is indicated at the left (0.06–16 cycles/degree), 60% contrast. The values in microvolts represent the respective response amplitude at 7.8 Hz (corresponding to four peaks per sweep) as calculated by Fourier analysis. The subject in the left panel shows a unimodal tuning curve, whereas the subject in the right panel shows a bimodal tuning curve with a minimum at about 1 cycle/degree.



*Fig. 2.* VEP amplitude vs spatial frequency of all 22 subjects in the cross-sectional study, 60% contrast. Response amplitudes, extracted by Fourier analysis from the recordings (averaged over all four repetitions) at the specific spatial frequencies, are connected by straight lines. Curves are arranged somewhat arbitrarily from bimodal (top) to unimodal (bottom). The small horizontal bars on the left indicate the respective zero voltage. There are marked interindividual differences in amplitude and shape, especially with respect to the occurrence and depth of the 'notch' and with respect to the slope in the high spatial frequency region.



*Fig. 3.* VEP amplitude vs spatial frequency in all 13 subjects in the longitudinal study. Curves from eight recording sessions are superimposed for each subject. Subjects are arranged such that the variability index increases from top to bottom. Absolute amplitude can vary highly between sessions; the overall shape, however, remains fairly constant between sessions.

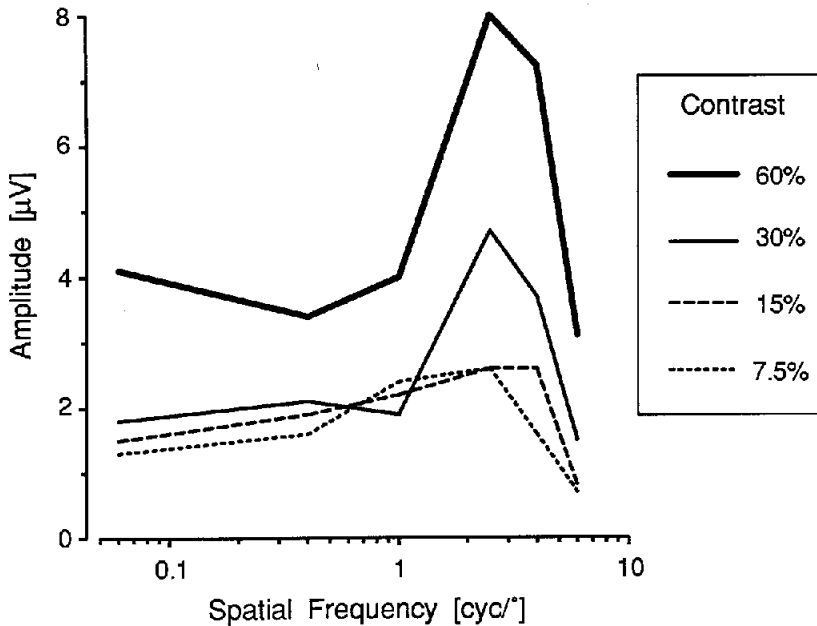


Fig. 4. VEP amplitude vs spatial frequency in one subject (second from bottom in Fig. 3) at four different contrast levels. For high-contrast levels the curve shape displays a marked 'notch' below 1 cycle/degree, whereas it becomes unimodal for contrast levels of 15% and below. At all contrast levels the low spatial frequency response is attenuated.

response at about 1 cycle/degree. Interestingly, the first distortion component ( $2 \times 7.8 \text{ Hz} = 15.4 \text{ Hz}$ , corresponding to eight peaks per sweep) had a less pronounced minimum.

Figure 2 depicts the tuning curves from all 22 subjects in the cross-sectional study. A large variety of shapes in the VEP tuning curve was obvious. All subjects had normal transient checkerboard VEPs with respect to latency and amplitude. Yet the tuning curves presented a continuum of shapes from almost flat (lower part of figure), through inverted U-shaped (middle) to bimodal (upper part). The slopes differed widely in the high frequency region.

Figure 3 depicts the results from the longitudinal study. In some subjects, the tuning curve was highly reproducible in shape and amplitude over eight sessions (positioned in lower part of figure), while in others the results varied widely. However, most of the variability can be ascribed to a scaling of amplitude with the same factor common to all spatial frequencies. Thus, the shape remains constant in most subjects, while absolute amplitudes may vary widely.

The presence of the 'notch' depended strongly on the contrast level of the stimulus. The results (Fig. 4) indicated that at contrast levels of 15% and less the shape of the tuning curve becomes unimodal.

## Discussion

This study demonstrated that the VEP tuning curve at high contrast shows marked interindividual differences. The curves in Fig. 2 show a variety of shapes and cannot easily be arranged along one dimension. The upper half of the curves could roughly be classified as bimodal, and the lower half as unimodal. This observation is consistent with findings of our previous report, which was based on a smaller sample size [8]. The longitudinal study reveals that the shape of the tuning curve is individually fairly constant (at least over 1 month) while absolute amplitudes can vary widely.

Some of the discrepancy in the literature regarding the shape of the tuning curve can be traced to differing contrast levels. Nakayama and Mackeben [9] (in monkeys) and Strasburger et al. [6, 10] (in humans) measured the complete response surface with regard to contrast and spatial frequency. They found a unimodal shape at threshold contrast and a pronounced notch at high contrast ( $> 20\%$ , see also our Fig. 4). Our findings suggest that discrepancies regarding the shape of the VEP tuning curve at high contrast may be traced to the large interindividual variability in combination with the small number of subjects in many of the previous studies.

Rather than using sinusoidal stimulation, we stimulated with square-wave gratings, which are spectrally less pure. Nevertheless, a 'notch' can occur, such as was reported in several studies utilizing sinusoidal stimulation [4, 11, 6]. However, when checkerboard stimuli with their richer spectrum are used, 'notches' are more seldom observed [8].

The high interindividual variability of the VEP amplitude might be due to anatomical factors [12] but this would introduce a constant scaling factor irrespective of spatial frequency. Why is the VEP tuning curve at low contrasts fairly similar between subjects but at high contrasts widely divergent (Fig. 2)? This has no correlate in psychophysical suprathreshold contrast perception: The function describing perceived contrast vs spatial frequency does not show any notches such as in the VEP tuning curve, but it becomes flatter with increasing contrast [13, 14]. The present study shows that about 50% of the subjects have a notch and that the shape of the tuning curve is an individual constant, but does not clarify the origin of a notch. Speculations regarding the cancellation of mass responses from different cortical sites have been disputed by Nakayama and Mackeben [9]. In

addition to the presence of the notch, a further discrepancy is evident between electrophysiological recordings and psychophysical thresholds: for temporally modulated sine or square wave gratings, contrast sensitivity remains constant for spatial frequencies below 1 cycle/degree [15]. Contrary to this, VEP amplitude does exhibit a low spatial frequency attenuation for dynamic presentation, both for sinusoidal gratings [6] and square-wave gratings (Fig. 2).

Generally, these findings emphasize that, above threshold, there is not necessarily a simple relationship between psychophysics and VEP-based electrophysiology [16, 17, 18].

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