Assessment of the visual acuity of human color mechanisms with the visually evoked cortical potential

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The amplitude of the human visually evoked cortical potential (VECP), which has been shown to vary as a function of the dimensions of checks in a checkerboard pattern, was used to objectively assess the visual acuity of the blue-sensitive compared with the red- and green-sensitive mechanisms in the eye. The results agree with psychophysical measures which have indicated poorer acuity of the blue system compared with the red and green systems.

Key words: visually evoked cortical potential, visual acuity, chromatic mechanisms, “sustained” neural pathways

It is well established that there are three chromatic mechanisms which govern human color vision. It is now also known that there are three classes of receptors differing in terms of the part of the visible spectrum to which they are maximally sensitive. These three cone photopigments have been termed blue, green, and red sensitive, with peak sensitivities at about 440 nm, 535 nm, and 570 nm, respectively. Stiles1–2 has devised a psychophysical procedure which allows one to selectively depress the sensitivity of any two of these chromatic mechanisms, leaving the sensitivity of the third largely unaffected. He has shown, for example, that an intense yellow background will lower the sensitivity of the red and green systems but leave the blue system basically untouched. Thus the spatial and temporal properties of an “isolated” chromatic system can be determined by the appropriate combination of a monochromatic test stimulus superimposed on a monochromatic background. Stiles has used the label \( \pi \) mechanisms to designate the blue \((\pi_1 \text{ and } \pi_3)\), green \((\pi_4)\), and red \((\pi_5)\) sensitive color systems because it was not clear if they could be directly related to the action spectra of the cones. Recent data indicate that these \( \pi \) mechanisms are closely linked to the spectral sensitivity of the cone photopigments.3–4

Studies of the “isolated” red and green mechanisms have generally found the spatial and temporal characteristics of these two systems to be quite similar.5–8 On the other hand, the isolated blue mechanism exhibits many anomalies. The unusual behavior of the blue mechanism seems to be related to two factors. First, apparently less than 10% of the cones in the monkey retina are blue sensitive.9 Human psychophysical studies reveal that the very center of the fovea may lack...
blue cones entirely, with the peak concentration occurring around 1 to 2 degrees from the center.\textsuperscript{10-12} This apparent scarcity of blue cones could account for the poor visual acuity of the blue mechanism noted in psychophysical studies.\textsuperscript{13-14} Second, ganglion cell recordings from monkeys seem to indicate that neural signal from blue cones are limited exclusively to the “sustained” pathways in the visual system.\textsuperscript{15} (See Breitmeyer and Ganz\textsuperscript{16} for a review of the properties of the “transient” and “sustained” neural systems.) This result could explain the low temporal resolution of the blue system and the finding that the blue system apparently contributes little to achromatic brightness.\textsuperscript{17-21}

When the visually evoked cortical potential (VECP) is recorded under the precisely controlled conditions typically employed in psychophysical studies, electrophysiologically measures often accurately parallel psychophysical data,\textsuperscript{22-25} although there are some exceptions.\textsuperscript{26} A number of studies have reported that the VECP is more sensitive to stimuli that are spatially structured, such as gratings or checkerboard patterns, than to unstructured stimuli.\textsuperscript{27,28} A report by Estevez and associates\textsuperscript{29} on the VECP spectral sensitivity of the chromatic systems noted that the spatial properties of the blue-evoked potential appeared to differ from the green- or red-evoked potentials. These findings suggested to us that the VECP could be employed as an objective measure of the visual acuity of the blue compared with the red and green mechanisms. In this study we were interested in whether measures of visual acuity derived from VECP amplitude measures would indicate a lower acuity of the blue mechanism and to what extent the VECP estimates would correspond with psychophysical measures of the acuities of the blue vs. the red and green systems.

Materials and methods

Three adult subjects, one man and two women, participated in this study. They all evidenced normal color vision as indicated by a number of standard color vision tests and were corrected to at least 20/20 (6/6) Snellen acuity. All three had been involved in previous psychophysical and VECP experiments.

The stimuli were presented monocularly in Maxwellian view and consisted of a 24° circular background onto which a 6° central circular test target was flashed for 100 msec every second. The target (TF) was either a checkerboard pattern with check size varying from 5’ to 80’ or a blank field of matched mean luminance. The luminance and spectral characteristics of the TF and background could be precisely controlled. An achromatizing lens was used to correct for the chromatic aberration of the eye. To isolate the blue mechanism, a 450 nm TF was presented on a 575 nm background of 4.6 log trolands. The red-green system was stimulated using a 575 nm TF on a white background of 4.1 log trolands. Psychophysical increment spectral sensitivity functions collected on each subject showed a maximum sensitivity at 440 nm, with a 2 log unit decrease by 520 nm, when the yellow background was used, indicating that we had indeed “isolated” the blue system. Additionally, psychophysical t.v.c. curves indicated that we were stimulating the blue mechanism termed $\pi_3$ by Stiles.

The EEG was recorded by means of scalp electrodes, with the active electrode at Oz, the reference electrode on the right earlobe, and the ground electrode on the forehead. These biopotentials were amplified (bandpass of 0.1 to 100 Hz) and were continuously displayed on a polygraph. They were then led to a digital minicomputer for on-line averaging. Each VECP resulted from 100 TF presentations, and each waveform was preserved in digital form in the computer’s mass storage device.

At the beginning of each session the subject adjusted a neutral-density wedge to determine his or her increment threshold for both the blue and yellow TF on the appropriate background. The TF was then maintained at a level 1 log unit above this threshold for the duration of the session. A typical session began with 5 minutes of dark adaptation followed by 2 minutes of light adaptation to, say, the yellow background, and then the first VECP to the blue TF was recorded. The check size of the TF was then changed and the second VECP recorded, and so on, until the eight check sizes and the blank field were presented. The background was then switched to white, followed by 2 minutes of light adaptation, and the yellow TF was used to record VECPs for the eight check sizes and the blank field. Thus a total of 18 trials were run in each session. Within a session the different check
sizes were presented in a preset random order and this order was changed for each session. The order of the two TF/background conditions was alternated from session to session over the four sessions for each subject.

After four sessions had been completed, the VECP waveforms for each treatment combination were pooled, resulting in 18 VECP waveforms with a sample size (n) of 400 for each subject. These waveforms were plotted on an X-Y plotter and digital values were printed on a line printer. Computations of amplitude and latency of the major deflections were made from the digital printouts.

**Results and discussion**

Fig. 1 shows the pooled waveforms for subject AMC. It can be seen that as check size is varied, there are systematic changes in the amplitude of the VECPs for the blue and red-green systems. Additionally, compared with the red-green responses, the blue mechanism's VECPs are less complex in appearance and show longer implicit times for the peaks labeled B and C. For subject AMC, the implicit time difference of peak B is about 40 to 50 msec. Similar values were found for the other two subjects. This difference in implicit time is consistent with the notion that the blue mechanism is a temporally delayed system.

The amplitude measure B-C of the VECP is plotted as a function of check size in Fig. 2. These functions are shown for each of the three subjects in the left panel. Since we found similar functions for all three subjects, the data were pooled and are displayed in the right panel. Two features of these plots stand out: (1) it takes a larger check size to produce maximal VECP amplitude for the blue mechanism than for the red-green mechanism and (2) the blue mechanism manifests a broader spatial tuning curve than the red-green mechanism.

We employed the following rationale to use the VECP as an objective measure of the acuity of the blue vs. the red-green mechanisms. First, we reasoned that when the checks were so small as to be subjectively unresolvable, then the amplitude of the VECP should be the same as that produced by a blank field of matched luminance. Secondly, it appeared to us that there was a linear decrease in VECP amplitude from its maximum at the 24° or 36° check size to a minimum at the 5' check size. We therefore fitted linear regression lines by the method of least squares to the blue and to the red-green pooled data as indicated by the dashed lines in Fig. 2. Taking the amplitude value for the blue or red-green blank field VECP, which corresponds to a check size of 0', and setting it equal to Y in the regression equation gave us a check size which is the electrophysiological analog to psychophysically determining when a pattern becomes indistinguishable from a uniform field. This extrapolation method has been used to estimate acuity in cats and in human infants. The equation for the blue mechanism was $Y = 0.18X + 4.77$ and for the red-green mechanism $Y = 0.44X + 6.74$. The correlation coefficient $r$ was 0.97 for the blue and 0.98 for the red-green system, indicating a good linear fit. We com-

![Fig. 1. Pooled VECP waveforms for subject AMC](https://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/933314/)
Fig. 2. VECP amplitude as a function of check size. The left panel shows data from each of the three subjects; in the right panel these data are pooled. Open symbols represent the red-green mechanism and filled symbols represent the blue mechanism.

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