An objective method for color vision deficiencies measurement based on visual evoked potential

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The equi-luminance of color stimulus in normal subjects is characterized by L-cone and M-cone activation in retina. For the protanopes and deuternopes, only the activations of one relevant remaining cone type should be considered. The equi-luminance turning curve was established for the recorded visual evoked potentials (VEPs) of the luminance changes of the red and green color stimulus, and the position of the equi-luminance was used to define the kind and degree of color vision deficiencies. In the test of 47 volunteers we got the VEP traces and the equi-luminance turning curves, which was in accordance with the judgment by the pseudoisochromatic plate used in clinic. The method fulfills the objective and quantitative requirements in color vision deficiencies test.

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Normal color perception depends on the absorption of photons by the three classes of cone photoreceptor in the retina. As the peak sensitivities of the three cones, it is convenient to refer to the three types of cone as S-cone, M-cone, and L-cone respectively[1]. But any malfunction of the cones can lead to abnormal color appreciations. They are called color vision deficiencies. Many forms of them are congenital in origin, although it can be acquired as a result of eye disease, or as a side effect of medication. 8% of men and 0.5% of women are color deficient. There are more than 100 professions from which color-deficient people are excluded. In recent times the amount and significance of information sent by color has grown. It was observed that color-deficiency has a negative effect on clear sight and noticing details.

Clinical color vision testing has some limitations in the diagnosis of color deficiency. For example, Ishiara test uses a pattern of dots of different sizes which in combination construct a symbol against a background. And the anomaloscope requires individuals to match a standard yellow color against that of a red/green mixture[2]. All these methods belong to the psychophysical test and can be cheated. So the purpose of the current study is to develop an objective and quantitative color vision test.

So we make the focus on the visual electrophysiology testing. It includes three forms: electro-oculogram (EOG), electroretinogram (ERG), and visual evoked potential (VEP). VEP is an evoked electrophysiological potential that can be extracted, using signal averaging from the electroencephalographic activity recorded at the scalp. VEP can provide important diagnostic information regarding the functional integrity of the visual system[3,4].

It is known that for the luminance changes of the red and green color stimulus, the S-cone contribution can be neglected[5]. So the equi-luminance of color stimulus in normal color vision is characterized by L-cone and M-cone activation. And for the protanopes and deuteranopes, only the activations of the one relevant remaining cone type have to be considered. If the equi-luminance turning curve was established, the position of the equi-luminance can be used to define the kind and degrees of color vision deficiencies. We established the curve by the way of chromatic visual evoked potential (CVEP) measurement. In this measurement, the chromatic pattern reversal stimulus consists of red and green that change phase abruptly and repeatedly at a specified number of reversals per second.

Our system of VEP measurement is shown in Fig. 1. The chromatic stimuli were presented on a cathode-ray tube (CRT) display controlled by main station. When the subject watched the changed stimuli, the evoked potential can be extracted by two measurement channels with standard electrodes connected to the visual electrodiagnostic system. Standard silver-silver chloride disc surface electrodes were used to recording VEPs. Conformed the international standards (the International Society for Clinical Electrophysiology of Vision, ISCEV), the active electrode was placed on the scalp over the visual cortex at Oz (inion up 2 cm) with the reference electrode at Fz (forehead up 4 cm)[6]. The visual electrodiagnostic system included amplifier, filter and A/D converter, and was controlled by the main station.

Figure 2 shows the sample of chromatic stimulus. If the luminance of the red patterns was E_{R}, that of the green parts was E_{G}, and the total luminance of the visual area was E_{T}, the red luminance ratio can be defined as

$$T = \frac{E_{\mathrm{R}}}{E_{\mathrm{R}} + E_{\mathrm{G}}} = \frac{E_{\mathrm{R}}}{E_{\mathrm{T}}}. \tag{1}$$

Keeping the hue of individual squares held constant (in our experiment the chromaticity coordinate of patterns

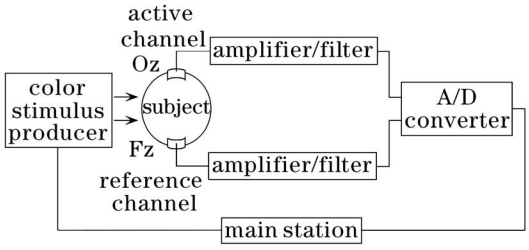

Fig. 1. Constitution of color vision deficiencies testing system.

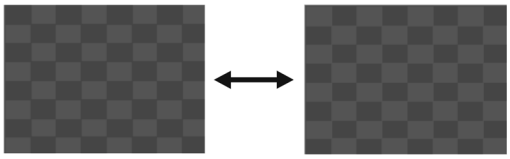

Fig. 2. Sample of chromatic pattern ($T = 0.5$).

were $x_R = 0.661$, $y_R = 0.346$, $x_G = 0.303$, $y_G = 0.591$), the respective cone activations L, M, S can be obtained by the Smith-Pokorny transformation[7]

$$\text{Red}: \begin{pmatrix} L_R \\ M_R \\ S_R \end{pmatrix} = T \begin{pmatrix} 24.4 \\ 5.62 \\ 0.03 \end{pmatrix}, \tag{2}$$

$$\text{Green}: \begin{pmatrix} L_G \\ M_G \\ S_G \end{pmatrix} = (1-T) \begin{pmatrix} 18.5 \\ 11.5 \\ 0.40 \end{pmatrix}. \tag{3}$$

And the S-cone contribution can be neglected. So the equi-luminance points can be calculated by

$$L_R + M_R = L_G + M_G. \tag{4}$$

So to the normal color vision person:

$$T_E(24.4 + 5.62) = (1 - T_E)(18.5 + 11.5) \Rightarrow T_E \cong 0.5. \tag{5}$$

To the protanopes:

$$M_R = M_G \Rightarrow 5.62T_E = 11.5(1 - T_E) \Rightarrow T_E = 0.67. \tag{6}$$

To the deuteranopes:

$$L_R = L_G \Rightarrow 24.4T_E = 18.5(1 - T_E) \Rightarrow T_E = 0.43. \tag{7}$$

At the same time, the anomalous trichromat whose color discrimination was between the normal trichromat and dichromats has the anomalous L-cone or M-cone. So the value of equi-luminance was in the scale of all. Thus it can be seen, the equi-luminance T_E can be taken as the parameter of the color vision deficiencies. The equi-luminance turning curve can be established by the VEP measurement of each red luminance ratio, the dip position of the curve was the equi-luminance of subject.

At the beginning of measurement, the red squares have the maximal luminance and the green squares have the minimal luminance. In other words, $E_R = E_T$ and $E_G = 0$. The total luminance of patterns E_T would be held constant. And the luminance of the red and green parts would be varied in opposite direction from minimal to maximal luminance. At the end of this process, the luminance distribution would be changed to $E_R = 0$ and $E_G = E_T$. So the red luminance ratio T was changed from 1 to 0. For each luminance ratio, the VEPs would be recorded through the electrodes in the subjects scalp when the subjects see the chromatic stimulus. So the equi-luminance turning curve was established, and the parameter of color vision deficiencies was measured.

In our study, there were 31 males and 16 females in volunteers joining in the VEP test. Age ranged from 20—25, acuity was better than 1.0. In all subjects the diagnosis was based on Yuziping pseudoisochromatic plate testing. There were 36 normal subjects, 4 dichromats, 7 anomalous trichromats. In the experiment, the chromatic stimulus consists of red and green checkerboards which had 16×16 parts and sizes were 15×15 (mm). The frequency of the pattern reversal was 10 Hz, and the sampling rate of the VEPs was 1024 Hz. For de-noising, the progressive mean was used. The number to average was 100 points, the unit sampling period was 500 ms. Distance from CRT to subject was 85 cm.

Figure 3 shows the original recordings from a normal color vision subject. VEP traces and the corresponding Fourier spectra were presented at the pure luminance conditions ($T = 0$, Figs. 3(a) and (b)) and at subjective equi-luminance ($T = 0.5$, Figs. 3(c) and (d)) for normal. At the pure luminance conditions (at the beginning or the end), a strong stimulus response is seen in the Fourier

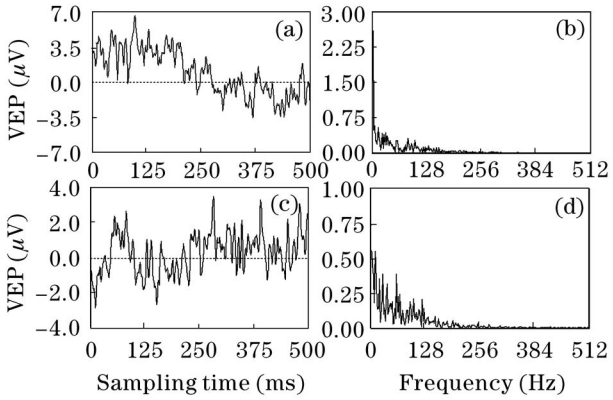

Fig. 3. VEP traces and FFT results for normal subjects.

Table 1. Grand Average Result for Normal Subjects

Red Luminance Ratio (T)	Relative VEP ($n = 36$, $\bar{x} \pm s$)
0	0.98±0.13
0.30	0.76±0.20
0.40	0.74±0.17
0.42	0.30±0.09
0.44	0.26±0.14
0.46	0.31±0.10
0.48	0.22±0.06
0.50	0.21±0.25
0.52	0.23±0.21
0.54	0.39±0.17
0.56	0.34±0.17
0.58	0.65±0.25
0.60	0.54±0.27
0.62	0.81±0.04
0.64	0.79±0.27
0.66	0.82±0.16
0.68	0.85±0.13
0.70	0.96±0.08
1.00	0.95±0.11
Equi-Luminance Point (T_E)	0.50

($\bar{x}$: the mean value, s: the standard deviation)

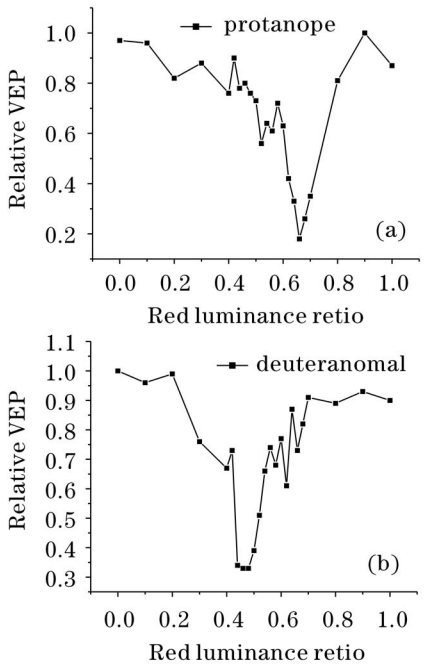

Fig. 4. Equi-luminance turning curves.

spectrum at a frequency of the pattern reversal (10 Hz). At equi-luminance the VEP amplitudes drop down to noise level.

For each subject, the VEP value was obtained from fast Fourier transform (FFT) at each luminance condition. After the normalization, the result of normal color vision volunteers on an average was shown in Table 1.

Totally, the equi-luminance turning curves of the results for color vision deficiencies subjects are given in Fig. 4. Figure 4(a) showed the measurement result of the protanope. The dip point ($T_{\rm E} = 0.66$) was very near the theory position. And Fig. 4(b) showed the result of deuteranomal. The types of the color vision deficiencies defined by the equi-luminance point ($T_{\rm E} = 0.48$) was in accordance with the judgment by the pseudoisochromatic plate used in clinic.

On the basis of the chromatic visual evoked potential measurement of the normal color vision person and color-deficient person, we have established the equi-luminance turning curves of these volunteers. From the curves, the kind and degree of the subjects can be defined. This novel method for color vision deficiencies fulfills the objective and quantitative requirements in color vision deficiencies test. The measurement based on VEP is much better than the clinical color vision testing method. It would become the main technology of the research on color vision and the testing for color vision deficiencies.

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