References

1. A. P. Altshuller and I. R. Cohen, *Intern. J. Air Water Pollution* **8**, 611 (1964).
2. B. E. Saltzman, *Anal. Chem.* **26**, 1949 (1954).
3. J. J. Bufalini and E. R. Stephens, *Intern. J. Air Water Pollution* **9**, 123 (1965).
4. J. F. Brown, *J. Am. Chem. Soc.* **79**, 2480 (1957).
5. O. P. Strausz and H. E. Gunning, *Can. J. Chem.* **41**, 1207 (1963).
6. C. S. Tuesday, in *Chemical Reaction in the Lower and Upper Atmosphere*, R. D. Cadle, Ed. (Interscience, New York, 1961), pp. 1–49.

13 September 1965

Evoked Visual Potentials and Human Color Vision

Abstract. *The waveform of the evoked visual potential is color specific. This specificity is absent in a color-deficient observer.*

There is a long history of attempts to develop objective means for gauging individual differences in human color vision. Such reflexes as the pupillary and the optokinetic have been tried with no genuine success. More recently, the single-flash electroretinogram has been used but with only a little more efficiency.

Some laboratories are now studying evoked occipital potentials. General agreement on two important facts is emerging. (i) The evoked occipitogram reflects primarily foveal luminosity characteristics (*1*); and (ii) because of this foveal bias, the occipitogram may bear a closer relationship to visual psychophysics than any other electrophysiological measure yet obtained in man (*2*).

We give here the results obtained from three highly trained observers (ourselves). Our data have revealed an important color and individual specificity in the waveform of the evoked response which has not been reported (*3*). This report covers the following kinds of light: xenon white, and colors of wavelengths (in nanometers) of 680, 575, 520, and 400, obtained with narrow-band interference filters. The colors, a deep red, a yellow-green of minimum saturation, a rather full green, and a blue-violet, were chosen with some care.

One point must be made about method—studies of visually evoked-potentials should be done with Ganzfeld or Maxwellian-view stimulation. With the first method the whole eye is filled uniformly with light, and with the second the image of the source itself is placed within the pupil of the subject's eye. We have used the Maxwellian-view technique. By no other method have we been able to obtain the reliability which we can now report.

We use a 500-watt xenon lamp as our source. A rotating aperture disc exposes the light for approximately 0.01 second. The waveform of the flash is flat-topped and rises and falls gradually. The stimulus duration is very much longer than that more typically obtained with the widely used electrical discharge lamps (for example, the Grass PS2 has a flash lasting 10 μsec), and this longer flash duration could be an important factor in our results. However, as with discharge lamps, we are also using a stimulus waveform which has both on-and-off characteristics, and we are aware that our results may be further complicated by this fact (*4*). Although controlling the light flashes mechanically sacrifices some of the exactness obtainable electronically, it has one important ancillary advantage. There is no audible discharge click synchronous with the flash. Our subjects hear only a low steady rumble. Evoked auditory potentials are very large, and it is well known that they can contaminate the visual response. Our method avoids such intersensory influences.

The disc cuts the light beam at a focus and the beam then passes through a camera shutter. This shutter is closed between test runs to allow for control of the observer's dark- and light-adaptation. The beam is collimated

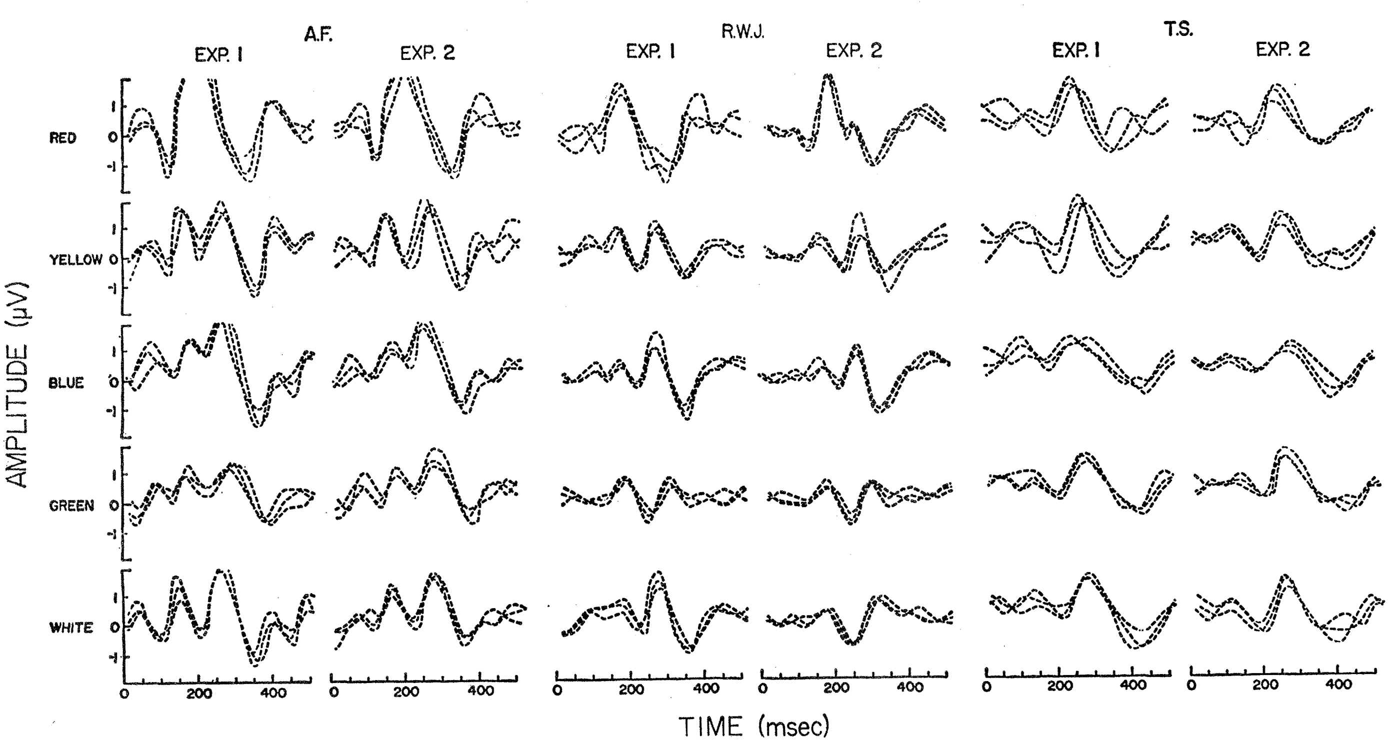

Fig. 1. The chromatic evoked occipitogram in man. A.F. and R.W.J. are color-normal observers, and T.S. is a deutan observer. In experiment 2 observations on R.W.J. were taken with the electrodes at 5 mm separation.

and passes through an interference filter. A set of calibrated neutral density filters and a calibrated neutral density wedge provide continuous brightness control over about 10 log units. In accordance with methods developed by us (*5*), this instrument is a dark-adaptometer as well as a stimulator for use in studies of evoked potentials.

The light then passes through two lenses which form an image of the source in the pupillary plane. This image is approximately 1.5 mm in diameter; it fits inside the subject's natural pupil which, under all our conditions, is over 3 mm in diameter (*6*). A field stop controls the stimulus size (11°). The size chosen covers the foveal region and substantially eliminates the effect of stray light there. Whatever stray light effects do occur will be mediated by the rod system, and the evoked occipitogram is less influenced by rods than by cones. A small fixation point is located in the middle of this field. The observer is shielded from all extraneous room light.

A flat glass plate placed in the beam just after the shutter acts as a partial reflector and deflects a synchronous light pulse that is focused on a photocell, which, in turn, is connected to the computer (TMC Syber-Neurac). The evoked occipitogram appears on an oscilloscope screen from which it may be traced or photographed. The occipital electroencephalogram of the subject is monitored on a second oscilloscope. Two electrodes are used: one at the occipital pole and one 8 mm directly above it (*7*). The ground is attached to the ear.

We first measured the absolute threshold for a color and then obtained the evoked occipitogram for the same color at an intensity exactly 2.5 log units above threshold. Both measurements were preceded by identical periods of adaptation: light adaptation for 30 seconds to 171 photopic ca/m^2, followed by dark adaptation for 60 seconds. Each determination took approximately 20 to 25 seconds, after which the subject rested for about 5 seconds, and then reentered the light-adaptation phase. Thus we specified and equalized the stimulus intensities according to the momentary thresholds for each observer for each color. These thresholds differed significantly for each observer and for each color, but from day to day, and even week to week, they agreed within observers and colors to approximately 0.1 log unit. The observer was completely at rest (supine on an examining table) during the experiment while the light entered the eye along the upward-directed primary line of sight. The head was held firmly and comfortably in the Maxwellian-view position by a special restraining pillow (*8*).

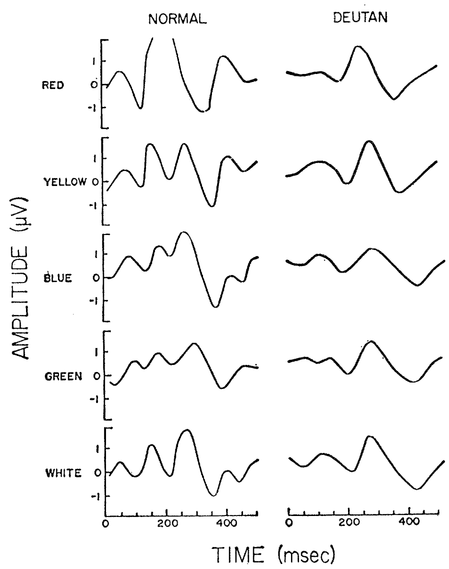

Fig. 2. Representative chromatic occipitograms for a color-normal and a deutan observer.

Our evoked occipitogram is the linear sum of 32 responses, electronically filtered outside a narrow 2- to 40-cycle band-pass. We presented the flashes at a rate of 2 per second and examined a period of 500 msec from the start of the flash. An experimental session consisted of one threshold determination and three occipitogram determinations for each of the five colors.

Each run was 2 minutes long. A control run was taken in which no light reached the observer's eye. Finally, the first threshold measurement was retaken. No progressive changes in adaptation occurred during the experiment.

Our results, for two separate experiments for each observer, are given in Fig. 1. The deutan observer is T.S.; observers A.F. and R.W.J. are both color-normal observers (according to American Optical Co. Hardy-Rand-Rittler, 100-hue, anomaloscope, and other tests) but they do disagree on the exact anomaloscope setting (within a few points, but consistently) and on the position in the spectrum of the pure green hue (*9*). Examination of the data for a given color shows marked similarity between the two normal observers. Those differences which do exist, for green especially (*10*), are primarily amplitude differences rather than differences in pattern. We are not certain that these differences are related to the psychophysical differences between these observers since differences of other kinds do exist (skull and brain anatomy and sex); but if they are related to psychophysical differences, it would seem that a new method for objective color psychophysics is at hand.

Unlike amplitudes in other electrophysiological waveforms, such as the oscillatory potentials of the human electroretinogram, those in the occipitogram can be repeated with results that agree rather closely from day to day for a given observer. Culmination times are even more reproducible ($\bar{\sigma}$ equals 7.6 msec). Comparisons between the separate waveforms reveal four or five distinct patterns (Fig. 2). Although we do not yet wish to make a point-by-point analysis of our waveforms [as Ciganek has, for example (*11*)], nevertheless we may note that there are certain consistencies which appear in the responses of *both* the color-normal observers. The red stands sharply apart from the other colors as revealed especially by its outstanding positive peak on the occipitogram at about 200 msec and its large negative trough at 325 msec. The yellow shows double positive peaks (165 and 275 msec) with an especially deep trough between them (220 msec). The blue differs from the yellow in that it has significantly smaller oscillations with the single exception of the major descending segment. The major green peak is significantly later than the comparable peaks in the other curves (at 300 msec).

Although the white and the yellow waveforms are similar, there is a tendency for the first trough for white in observer A.F. to appear early (100 msec). On the other hand the curves for green and for white for observer R.W.J. overlap closely so that we are not able to distinguish between them.

Finally, the occipitograms for different colors from the deutan observer are surprisingly indistinguishable. If superimposed, all curves would be approximately congruent. This response is in marked contrast to the responses from the color-normal observers and appears to indicate that the occipitogram is a diagnostic aid of some promise. It may be pertinent to note, however, that the deutan's responses to white do resemble those of R.W.J. in his first experiment.

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References and Notes

1. A. M. Potts and T. Nagaya, *Invest. Ophthalmol.* **4**, 303 (1965); J. Armington, *Proc. 3rd Intern. Soc. Clin. Electroretinography Conf.*, Highland Park, Ill., November 1964, in press.
2. J. B. Siegfried, D. I. Tepas, H. G. Sperling, R. H. Hiss, *Science* **149**, 321 (1965).
3. We are aware of a talk on this problem by M. Clynes *et al.* [*Federation Proc.* **24**, 274 (1965)], but the printed reports of this work which we have been able to obtain are difficult to evaluate. In a subsequent digest (*Intern. Conf. Med. Electron and Biol. Eng., 6th, Tokyo*, August 1965, pp. 460–461) Clynes does report (Fig. 4) some color-specific responses but does not give an indication of their reliability nor does he make a chromatic analysis.
4. M. Clynes, M. Kohn, K. Lipschitz, *Ann. N.Y. Acad. Sci.* **112**, 468 (1964).
5. T. Shipley, *Proc. 3rd Intern. Soc. Clin. Electroretinography Conf.*, Highland Park, Ill., November 1964, in press.
6. We have taken data on ourselves with dilated pupils, thus making the Maxwellian-view easier to hold, but we have not found any substantial change in our results; if anything, we find a slight loss in reliability. The Maxwellian-view technique will probably require pupillary dilation in untrained observers.
7. Electrode placement seems very important in this work. We have experimented with many positions and those used here give the best results for our present purposes. They may not do so for other purposes equally restricted to the visual system (for example, field studies). Different positions do work best for different subjects.
8. This is a rectangular plastic pillow filled with tiny glass beads (Flexicast, Picker X-ray Corp.). Upon air evacuation, it takes the shape of whatever is impressed into it and literally locks it in place.
9. M. Rubin, *Amer. J. Ophthalmol.* **52**, 166 (1961). It is possible that observer R.W.J. has some very mild color anomaly not apparent from usual testing procedures, or that he may be at one extreme of the normal range. On the contrary, the observer T.S. is clearly deuteranomalous, but to avoid exact specification of the extent of the deficiency at this time we use the term "deutan."
10. While these observers agree in white at 8 mm, R.W.J. disagrees with A.F. at 5 mm.
11. M. L. Ciganek, *Rev. Neurol.* **99**, 194 (1958).
12. Supported by contract DA-49-193-MD-2344 from the U.S. Army Surgeon General.

23 September 1965

Volume Measurements on Chromium to Pressure of 30 Kilobars

Abstract. *The unit cell volume of chromium was measured as a function of pressure from 1 bar to 30 kilobars by x-ray diffraction techniques. The antiferromagnetic transition occurred at 1.5 kilobars at 29°C, where there is a discontinuity in the slope of the curve for lattice parameter vs. pressure. By electrical resistance measurements the value of* $-\Delta T_N/\Delta P$ *was determined to be 5.9° ± 0.3° per kilobar. At room temperature chromium remains in the body-centered cubic crystal structure from 0 to 55 kilobars.*

A transition in Cr from the antiferromagnetic state to the paramagnetic state (the Neel point, T_N) has long been known and has been of interest to investigators. Bridgman noticed anomalies in certain properties of Cr as a function of pressure, notably in the electrical resistance and compressibility (*1, 2*). However, much of his data are inconsistent with the findings of recent workers, and it has been suggested that the inconsistency is due to the impurity content of his samples and to strains introduced into his pressure system (*3*). Since the time when our work commenced, several notes and articles have been published about Cr under pressure, investigations being made by means of electrical resistance (*3*), neutron diffraction (*4*), and ultrasonic vibrations (*5*). Our work concerns the volume anomaly in Cr at the Neel point.

We measured volume changes by x-ray diffraction techniques. Chromium powder was mixed with polyethylene powder, and the mixture was pressed together to give a sample (about 0.3 mm thick) containing about one absorption length (the thickness of chromium required to reduce the incident beam intensity by $1/e$) of Cr (0.05 mm). Besides providing a sample of workable thickness, addition of polyethylene served to improve the approximation to hydrostatic conditions in the solid pressure-system. This sample was then centered in either a boron-filled plastic tetrahedron or a lithium hydride tetrahedron and placed in the tetrahedral x-ray diffraction press (*6*). Molybdenum K_α radiation was used, and the five most intense lines of the Cr powder pattern, (110), (200), (211), (220), and (310), were monitored. Pressure was determined by means of the bismuth I-II transition at 25.2 kb in conjunction with continuous resistance

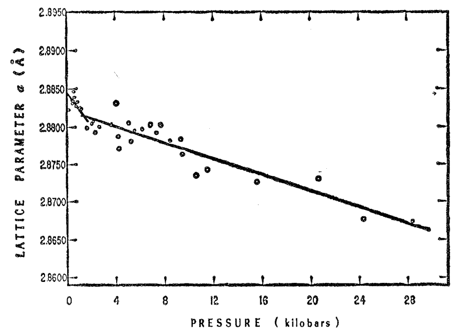

Fig. 1. Lattice parameters of chromium vs. pressure.

measurements of Yb which were related to NaCl compressibility as determined by x-ray diffraction (*7*).

For the determination of the lattice parameter as a function of pressure, the lattice parameters computed from the spacings (measured in two independent runs) of each of the five major Cr lines were averaged at each pressure setting. Thus each point in the curve of Fig. 1 is the average of ten measurements. The uncertainty in lattice parameter is of the order of 0.05 percent in the antiferromagnetic region and 0.10 percent the paramagnetic region. The extremely low compressibility of Cr makes measurement difficult. However, least-square fits of the points from 0 to 2 and from 28 kb show a clear break at 1.5 kb. Our electrical resistance measurements on Cr also indicate a transition (resistance discontinuity) at 1.5 kb. The temperature during these experiments was 29.0° ± 0.5°C. Litvin and Ponyatovskii (*4*), by studies of neutron diffraction and electrical resistance, found the transition at 38°C at atmospheric pressure and found $-\Delta T_N/\Delta P$ to be 5.9°/kb. This would put the transition at about 1.5 kb at 29°C, which is consistent with our data.

In the electrical resistance measurements on Cr we have found the atmospheric pressure Neel temperature to be 38.0° ± 0.5°C, in excellent agreement with the findings of other workers (*3, 4*). From these same measurements we determined $\Delta T_N/\Delta P$ to be 5.9° ± 0.3°/kb, again in agreement with the value of Litvin and Ponyatovskii (*4*) but slightly higher than that of Mitsui and Tomizuka (see *3*), who found 5.1° ± 0.2°/kb.

From the data of Fig. 1 we calculate a bulk compressibility in the antiferromagnetic region of $\beta_0 = 21.8 \times 10^{-13}$ (dyne/cm^2)$^{-1}$. In the paramagnetic region $\beta = 5.60 \times 10^{-13}$ (dyne/cm^2)$^{-1}$. The initial compressibility is larger than obtained by Bridgman (*1*), who found