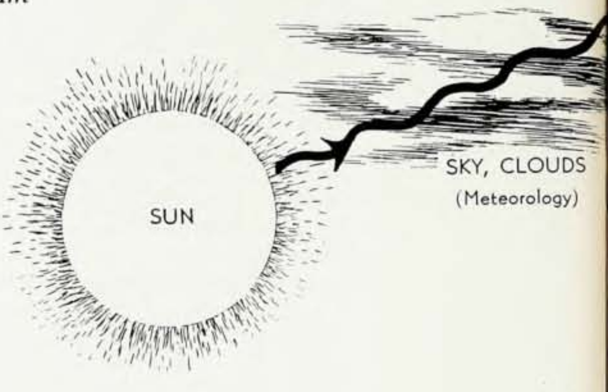
Color VISION

by David L. MacAdam



The 1947 International Conference on Color Vision at Cambridge, England, is reported and analyzed by a participant.

Tracing the working of any one of the human senses from a physical stimulus to its perception by man brings into play taxing problems which reach to the limits of knowledge in each of the sciences it touches. Vision—color vision—is a particularly complicated process to study. Physicists investigate light, how it is emitted, absorbed, reflected, and how it passes through space. Physicists and biologists study how it passes through the eye; biochemists, histologists, electrophysiologists, neurologists, and so forth, study how it is received by the nerve-sensitive retina and then passed on to the brain. Somewhere along the line the psychologist enters the fray.

When a meeting on color vision was privately arranged by a few English investigators in Cambridge, England, for the week of July 28 to August 1, 1947, almost one hundred physicists, physiologists, and psychologists met. After the interruptions of the war, they found it a welcome opportunity to exchange ideas and almost all of the leading investigators of color vision attended. They came from Egypt, France, Holland, Russia, Scotland, Sweden, and the United States. Among those from this country were Forrest L. Dimmick, Dean Farnsworth, Selig Hecht, Deane B. Judd, George Wald, and the author.

The prime fact that emerged from the meeting is that theories of color vision are more unsettled, in the light of new investigations, than they were before the war. The classical trichromatic theory, formulated by Young and Helmholtz, had withstood major alterations for over fifty years. It has now been challenged in some important respects. Briefly, this theory states that color vision arises from an ability in the eye to respond in three and only three different ways to colors. Separately, these responses result in the sensations of red, green, and violet. Other color sensations are presumed to arise from combinations of these three responses. Theories have arisen which dispute this explanation; none has ever unsettled it, though some, which deny that all kinds of colors can be produced by combining the three primaries, stoutly maintain their opposition. Now, though the classical theory survived the fundamental questioning with which it was greeted at the meeting, it may need to be considerably modified in detail. The conception taking shape is that the eye may contain as many as *seven* different color-would be as indescribable to us as was the difference between green leaves and red cherries which the color-blind chemist Dalton reported that he could not see.

The Trichromatic Theory Modified

W. D. Wright, of the Imperial College of Science and Technology, London, opened the conference by reviewing the present status of the trichromatic theory and concluding that it is a necessary hypothesis in explaining some of the facts in color vision, and that it is not inconsistent with many of the facts which remain. This view became the focal point of attack by dissenters with the trichromatic theory and the rallying point for supporters.

As described above, Polyak reported finding at least three distinct kinds of nervous connection to every cone. He suggested that these are adequate for color differentiation, and that a separate type of cone to respond to each of the primary colors is not needed. The heart of Polyak's explanation lies in the extremely complicated arrangement of nerve connections between the single kind of cone and the multitude of nerve cells intermediate between the cones and the optic nerve. These structures are shown in beautifully clear illustrations in Polyak's book, "The Retina," University of Chicago Press, 1941. Some of the intermediate nerve cells act as relays, some as analyzers and differentiators. Their connections form a complicated pattern of series-parallel arrangements which have been so incompletely studied that it is not now prudent to formulate any detailed theory of the transmission of chromatically-differentiated nerve pulses from each cone to the brain. What seems probable is that color-differentiated impulses travel along characteristically different patterns of nerve channels, though they use some parts in common.

Granit amplified and recorded the nerve currents by contacting separate fibers of the optic nerve of a cat with a micro-electrode. He found, as was said earlier, responses from seven processes having distinctly different spectral sensitivities, none of which could be compounded of the others. It is conceivable that these seven independent responses are reduced to three combinations of responses before they reach the optic nerve. Thus no contradiction with either the trichromatic theory or with Polyak's theory is implied.

An apparent contradiction did arise when George Wald, of Harvard, reported his findings on the minimum energy for various wave-lengths that can be seen with the small central region of the retina. His data can be represented by a combination of three sensitivity curves corresponding to the three primary colors only. However, Granit, in recording his seven different responses, did find two or three which predominated over the others. The apparent contradiction may thus be resolved when the two sets of data can be put on a more easily comparable basis than they are now.

Selig Hecht, of Columbia, gave a report which was more directly concerned with what we see than with how we see it. It was on the lowest level of response for normal and partially color-blind persons. He found that the fovea of the normal observer is everywhere in the spectrum more sensitive to light than is the fovea of the color-blind person. Hecht pointed out that although these results support Young's simple and direct theory of color blindness as a loss of a receptor system, that theory cannot account for the sensations reported by color-blind observers.

Deane B. Judd, of the National Bureau of Standards, was in agreement with Hecht that the trichromatic theory can explain most of the facts of color

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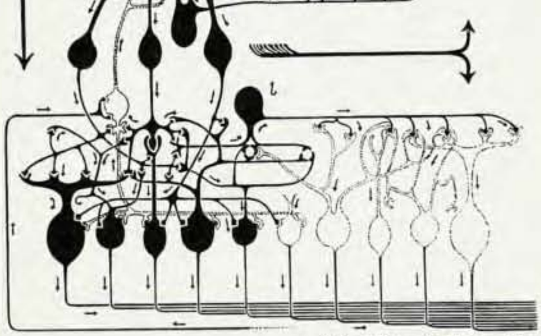

University of Chicago Press

Stylization, from Polyak's "The Retina," showing complicated nerve pattern for transmitting retinal impulses to the brain and back.

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blindness, with the notable exception of the sensations reported by partially color-blind persons. He indicated that a different form of explanation may be required for each of the various stages of the visual process: photosensitive reaction, receptor process, optic-nerve function, and brain function. He noted that the Hering opponent-colors theory seems to have value as a description of color processes in the optic nerve and in the brain. According to the Hering theory the fundamental sensations are the opposed pairs: red and green, yellow and blue, black and white. Each member of each pair has the effect of cancelling its complementary. Such opposition and cancelling may be indications of the patterns of optic-nerve channels used in transmitting the color responses.

A quantum theory of color discrimination was suggested by Hecht in reviewing the successes of the quantum theory of fluctuations of the absolute threshold of vision. Absorption of five or six photons, or quanta, of light by a single light-sensitive cell in the retina appears to be sufficient for the bare perception of a flash of light. Variations in this figure have been blamed in the past on fluctuations of biological sensitivity. Hecht felt they are fully explained by the purely statistical fluctuations of the number of quanta in flashes of light having such small average contents. Similarly, neighboring patches of uniform brightness can be barely distinguished when the difference in light energy received by the two adjacent rows of cones between which the boundary is focussed (during a critically short period) is five or six quanta. Hecht accounted for the differences in results obtained in repeated experiments, by the statistical fluctuations of such a small number of quanta. Hecht then suggested that color discrimination probably has a similar quantum basis. The spread of repeated determinations is similar in character to the spread of absolute thresholds and contrast thresholds.

Work on color discrimination was reported by others. The author described an experimental method for finding the limits of color discrimination when luminous as well as chromatic differences are simultaneously present. He also indicated a series of equally bright colors that yield equal visual acuity against gray backgrounds of the same brightness. A higher saturation of each hue is required to yield a higher acuity, but the ratio of saturations necessary for a required increase of acuity is the same for all hues. For every hue, the saturation necessary for any required acuity appears to be a constant multiple of the minimum saturation that is detectable from gray under the conditions most favorable for comparison.

W. S. Stiles, of the National Physical Laboratory, Teddington, presented a new formula for color discrimination for high brightnesses which fits well with the trichromatic theory. Stiles proposed his formula and discussed its implications in the Proceedings of the Physical Society of London, volume 58, pages 41 to 65, 1946.

The Trichromatic Theory Opposed

A number of papers representing a complete break with the trichromatic theory were given. The organizer of the conference, E. N. Willmer, of Cambridge University, suggested that there may be two kinds of rod in addition to the one kind of cone in the center of the retina. He explained lack of night vision in the center of the retina by saying that the capacity to accumulate large amounts of visual purple, which is necessary for night vision, is a specialized function of marginal rods and not an essential characteristic of rods. Willmer's hypothesis is discussed in detail in his book, "Retinal Structures and Colour Vision," Cambridge University Press, 1946. It seems impossible to account for color-matching data in terms of Willmer's theory, especially as the known spectral sensitivity of the rods cannot be compounded from those data. Consistency with color-mixture data is quite certainly a basic minimum requirement for a theory of color vision. There was also some discussion of color blindness at the very center of the retina (the fovea) which is very rich in cones, but this was disputed on the basis that the reports did not take into account the general loss of color discrimination when the test color patches are very small.

H. Hartridge, of St. Bartholomew's Medical College, London, marshalled a tremendous array of evidence in support of a polychromatic theory of color vision. He argued that the trichromatic theory is inadequate because almost none of the colors of the pure spectrum can be matched in saturation by a mixture of red, green, and blue (or violet) light. This is a generally acknowledged experimental fact, but is regarded as indicating only that the color sensitivities of all three receptor systems overlap throughout most of the visible spectrum, so that each is stimulated to some extent by the other two primaries. In Hartridge's opinion there are, in addition to those of the trichromatic theory, separate receptors for yellow, blue, orange, and blue-green. Hartridge's observations and arguments may be read in full in the Philosophical Transactions of the Royal Society of London, Series B, May 15, 1947.

As previously mentioned, development of true four-color vision would result in the emergence of entirely new color qualities, distinct from and in addition to hue, saturation, and brightness. Hartridge did not allude to any color experiences that are not describable in terms of those three attributes. So it seems safe to conclude that only three of the primaries of his polychromatic theory represent independent variables in the response transmitted to the brain. More efficient utilization of the seven independent responses detected in the retina by Granit will have to await fortunate mutations and further development of the already fantastically complicated nervous system of the eye.

The Cambridge Conference on Color Vision revealed considerable progress, during the war years, toward an understanding of color vision. Theories of color vision are becoming less speculative as experimental findings confine them within closer bounds, and there is a large basis of fact and interpretation on which the great majority of investigators are agreed. Significant researches are in progress, some suggested and all further stimulated by the Conference.

CONTRIBUTORS

Vannevar Bush resigned the vice-presidency of Massachusetts Institute of Technology to become president of the Carnegie Institution of Washington. During the war years he became a nationally known public figure as the result of his liaison work between science and Government as chairman of the National Defense Research Committee and then director of the Office of Scientific Research and Development. With the close of hostilities he has carried this public service forward as director of the Research and Development Board.

David Lewis MacAdam is a member of the Scientific Committee of the Kodak Research Laboratories and has been on the staff of the Physics Department since he received his doctorate from the Massachusetts Institute of Technology in 1936. In July 1947 he was sent to Cambridge, England by the Eastman Kodak Company to participate in the International Conference on Color Vision.

Arthur K. Solomon left Harvard with a doctor's degree in physical chemistry in 1937 and returned eight years later by a circuitous route that led him through the Cavendish Laboratory, the British Admiralty and Ministry of Supply, and the M.I.T. Radiation Laboratory. He is now Assistant Professor of Physical Chemistry in the Biophysical Laboratory at Harvard Medical School, where he is working on the application of isotopic techniques to biological problems.

Stephen White, principal science writer for the New York Herald Tribune, was appointed to that position because his city editor once saw him using a slide rule to calculate election-return percentages. His years of science writing have developed in him, he says, a wry affection and a qualified respect for physicists, both of which appear in his contribution to Physics Today.