

# Inter-Society Color Council *Newsletter*



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## ANNUAL MEETING SYMPOSIUM: ART AND SCIENCE IN THE USE OF COLOR

The title of the symposium scheduled for the Annual Meeting (April 13 and 14, 1970) has been changed from "The Role of Science in Art and Design" to "Art and Science in the Use of Color." This change has been made as a result of discussion among prospective panelists, who felt that the original title was too heavily oriented toward science. Evidently, a stimulating interchange of ideas has already occurred, and this fact portends a lively meeting.

An impressive array of panelists has been assembled by R. W. Burnham, symposium chairman, to analyze the subject matter: C. J. Bartleson, W. C. Granville, Anders Hård, Harry Helson, Dorothea Jameson Hurvich, A. A. Juliano, Jo Ann S. Kinney, C. S. McCamy, R. Spilman, and F. C. Wright.

## COLOUR GROUP AND ISCC PLAN JOINT PARTICIPATION IN GODLOVE-TYPE BIBLIOGRAPHY

We are pleased to announce that the Colour Group (Great Britain) plans to compile and publish a bibliography of articles on all phases of color, much like the Godlove Bibliography published by the Council many years ago. At the suggestion of the Colour Group, the Council has agreed to participate in the preparation of the Bibliography, which will be circulated both to the Colour Group in England and to the entire ISCC membership in this country. The following article has been circulated to the Colour Group under the title "Introduction to the Bibliography:"

"With the present bewildering proliferation of specialist journals it is becoming increasingly difficult to find published work even in one's own field and increasingly easy to miss papers of importance. Specialist abstracting services exist for a variety of disciplines but nothing comprehensive is available for the area in which the Group is concerned -- colour.

"The membership of the Colour Group covers a wide spectrum of interests and it is almost certain that between us in our reading we cover practically every

journal published in this country in which material relevant to colour appears. If this individual access to these specialist items was pooled and made generally available it could form the basis of a very broadly based and valuable bibliography. All that is required is the setting up of information handling machinery and a willingness on the part of individual members to participate. A list of titles could then be issued each month with the pink notice.

"A working party has been studying the possibility of setting up such a system and it seems quite practicable. It may be a novel concept for a learned society to adopt such an approach but the potential benefits make the attempt well worth while. During our preliminary discussions close contact has been maintained with the ISCC (U.S.A.) which has expressed not only interest but also a desire to participate and to cover journals published in the U.S.A. With this initial co-operation the scheme becomes potentially global in coverage and consequently of even greater usefulness. It is intended that the list of abstracts be printed both here and in the U.S.A. There is no doubt about the value of such a system -- the problem is how to set it up.

"The working party, with the support of the main committee, has drawn up proposals, which if supported by the Group as a whole, can ensure success for the venture. Enclosed is a list (naively believed to be comprehensive, but if there are omissions please indicate on the attached slip) of journals in which articles/papers on some aspect of colour have been published. Members who currently have access to some of these are asked to act as abstractors for at least one and to indicate their willingness to do so by completing the attached slip. The entries will consist only of title, author and journal reference of those papers, notes, new instruments or whatever, which are concerned with colour. These should be posted immediately the journal is published or sooner -- the essence of such an enterprise is that the information should be current, and to this end it is better not to have a precis of the article than to delay publication. From this point of view if abstractors have access to pre-publication information then the bibliography issued in say February could refer to material due to appear in March and so be of even greater usefulness. By this suggested wide distribution and simplicity of effort the task is kept to easily manageable proportions for any individual participating member while ensuring both a very broad coverage and small time lag in availability of information.

"The value of such a system is obvious. Its success rests entirely upon co-operation and involvement on the part of the Group membership as a whole and we urge you to help with the project by devoting a very modest amount of time each month to abstracting from a journal you know well. It is hoped to get the scheme operational by January 1970 and a prompt reply to this invitation is requested so that the deadline may be met. When the system becomes established we shall each be accumulating a very valuable, continuously updating and comprehensive bibliography of colour -- similar to the old 'Godlove.'"

There followed in the mailing to the Colour Group a request for bibliographers and a preliminary list of journals to be covered, numbering about 180. The list is known to be incomplete in many areas, particularly with respect to American publications. We anticipate circulating an amended list to ISCC members for additional suggestions in the near future.

Some additional ground rules of the Bibliography are:

1. We are going to do a straight bibliography: author's names, title, and journal citation, in standard form to be provided.
2. At this stage at least, no comments, ratings, or abstracts will be provided, to minimize time and effort of the bibliographers.
3. In the beginning there will be no division by subject, but each entry will be numbered to allow for periodic indexing.
4. Speed is of the essence to insure that the information is current.

The purpose of this note is to request ISCC members who read journals dealing with color to aid in the preparation of the bibliography on a continuing basis. If you are willing to help, please contact one of the following:

For the ISCC, Dr. Fred W. Billmeyer, Jr., Rensselaer Polytechnic Institute, Troy, New York, 12181.

For the Colour Group (Great Britain), Mrs. Dorothy I. Morley, Research Department, The Metal Box Company, Ltd., Kendal Avenue, London W.3, England.

A postcard or letter with your name, the names of the journals you would be willing to cover, and an indication if you have access to early or prepublication information, will suffice.

#### CMG ACTIVITIES

At their recent meeting in Miami Beach, the Color Marketing Group elected the following officers and directors:

President -- Jose Martin

Vice-President -- Ruth L. Strauss

Secretary -- J. Gibb Brownlie

Treasurer -- Kenneth L. Kelly

Directors -- Mrs. Donald Bender, Everett R. Call, Ralph J. Ceisler, J. B. Haverly, and Jack Sideman

Featured at the meeting was a special student seminar, attended by about 100 student participants, with presentations by Albert O. Halse and Alexander F. Styne.

#### THE COLOUR GROUP (GREAT BRITAIN)

Scheduled meetings for 1969-70 were reported in the Sept.-Oct. 1969 issue (#202) of the N.L. The following items will also be of interest to ISCC members.

The Scottish section will hold a symposium entitled "The Impact of Colour in Commerce" in Edinburgh University on 31st March, 1st and 2nd April, 1971. It is hoped to present papers on scientific or objective studies of colour in the fields of design, advertising, television, etc.

A colloquium will be held at the University of Glasgow from 17th to 19th August, 1970, on the subject of "Empirical Aesthetics."

Excerpts from the report of the Sixty-Third Science Meeting (Nov. 5, 1969) of the Group:

Dr. B. H. Crawford talked to the Group on "Lop-sided Ellipses of Colour Sensitivity." His study led him to conclude that the demonstrated phenomena "make nonsense of the present concept of uniform color space and also of the general use of MacAdam's ellipses as tolerance limits in the specification of colour." An "animated discussion" followed.

Dr. C. A. Padgham discussed "The Measurement of the Colour Sequences in the Positive Visual After-Image." He gave a "very convincing demonstration" of the sensation of light which persists in darkness after the cessation of a high-luminance stimulus. Using the binocular matching technique of Wright, he found the following general sequence in the after-images formed by exposure to a high-intensity white light: white, green, white, red-purple, blue-purple, and blue. With results transformed into the fundamental sensations suggested by Judd, the after-effects in the red and green processes were found to decay exponentially. The blue process is anomalous and gives an after-functioning curve which is initially weak, but rises to a peak of activity after about 60 seconds. A "lively discussion" followed this paper.

Other items from the Colour Group notice:

The MOM colorimeter, developed in Hungary for industrial use, is said to have unusual stability and to be a comparatively simple instrument. The instrument uses an annular selenium cell as the detector, has a viewing geometry of  $0^\circ/45^\circ$ , and accepts samples of any area between 5 and 45 mm diameter. Further details can be obtained from Miss A. R. Bugden, Industrial Communications Group, S.I.R.A., South Hill, Chislehurst, Kent, BR7 5EH.

Mr. M. Goodman, at Bath University of Technology, Department of Architecture, is engaged in a project concerned with intensive cattle housing. Any information concerning animal (particularly cattle) reactions to colour will be helpful. Address: 16 Lewington Road, Fishponds, Bristol.

#### REVIEWS OF:

Sheppard, Joseph J., Jr. Human color perception: A critical study of the experimental foundation. American Elsevier Publ. Co., New York, 1968. Pp. xvii + 192. \$10.00

(Ed. note: Sheppard's book has generated wide interest and various reactions, as indicated by the following four reviews, all by members of the ISCC. The subject matter is of such importance that your editor thought it useful to bring all four reviews together, even at the expense of some strain on the N.L. budget.)

Review by R. M. Evans. (By permission, Journal of the Optical Society of America, 1968, 58, 1422.

The world needs badly many more books of this sort on many subjects, although I would be the first to admit that the subject of vision has needed it more than most.

As the subtitle implies, this is a relatively fearless attempt to evaluate the literature containing the facts on which our knowledge of vision depends.

Most people will praise the author for a competent job very well done, some will feel that he has slighted or misunderstood their work, and a number will be misled by the main title.

By the use of the word "perception" Dr. Sheppard means to include practically everything the title would have meant if he had left out the word and called it "Human Color Vision." For that reason I feel I should report the chapter headings here.

After an introduction, which among other things says "the newcomer has a tendency to grossly underestimate the complexity of the subject . . .," there is a chapter on the process of color preception, then one on the

Standard Observer (CIE), then retinal sensitivity, retinal physiology, cerebral physiology, psychophysiology, temporal phenomena, and conclusions and recommendations. All of this is in a book of a little less than 200 pages, yet the reader has from it a clear view of how it all fits together and a bibliography of 245 books and articles for further reading. It is, to me, a remarkable accomplishment.

There are two items on which I should like to comment specifically. One appears to be an unfortunate error not due to the author and the other an omission for which he can hardly be blamed.

The apparent error is the attribution on page 129 of the "filling-in hypothesis" to Ditchburn. I am quite sure that this theory was first proposed by Gordon Walls. Dr. Walls was a good friend of mine and he possessed an almost encyclopedic knowledge of visual literature. When he published his very delightful article<sup>1</sup> on the subject, he made it quite clear that it was a new and daring hypothesis, although he gave excellent arguments to support it.

The second item, the omission, is one that I feel more strongly about than will most others. In my early studies on the subject of visual adaptation I encountered a remarkable doctoral dissertation by J. F. Schouten which colored a great deal of my thinking when I wrote the chapter in my book to which Dr. Sheppard refers. Unfortunately this dissertation was published<sup>2</sup> only in Dutch, although a short abridgment<sup>3</sup> of it was published later in this journal with Ornstein who was, presumably, his professor.

My regret comes from the fact that the original publication contained an hypothesis, omitted from the condensation, that I have more and more felt to be true. Schouten suggested that the process of essentially instantaneous adaptation (0.2 sec) is the mechanism that sends the visual message to the brain and that this is repeated at every blink or quick eye movement -- perhaps I am adding a little. But taken with Wall's filling-in process it has always seemed to me a rewarding line of thought.

I can recommend this book without reservation to any student, new or old, of the subject of vision. We all specialize and can gain much by a candid review of the other person's field.

I only regret that the author did not have available reports of some of my recent work. I should have been much interested in his comments.

<sup>1</sup> Gordon L. Walls, Am. J. Optometry 31, 329 (1954).

<sup>2</sup> Jan F. Schouten, Visuele Meting van Adaptatie en van de wederzijdse Beïnvloeding van Netvlieselementen, dissertation, (Drukkery Fa. Schotanus and Jens, Utecht, 1937).



Review by Leo M. Hurvich and Dorothea Jameson. (By permission, American Scientist, 1969, **57**(1), 143-166.)

The phenomena of color and color vision are largely in the public domain and they attract and intrigue layman and specialist alike. The specialists come from a wide variety of fields and occupations. In a highly developed industrial society like ours, interest in color is found at every stage of its many products as they pass from the manufacturer through the advertising media and display rooms and their ultimate purchase by the customer. Surrounded as we are by an infinitude of objects, from human hair to office buildings, that are dyed, painted, or impregnated with colorant material, it is little wonder that colorant formulas, color measurement, color specification, color standards, lighting, packaging design, color fading, etc., occupy the time and energies of countless technologists, engineers, production men, dyers, lighting specialists, television experts, decorators, designers, commercial artists, photographers, and salespeople.

The problems in this everexpanding commercial and technological use of color are fascinating and often difficult ones, but there are concerns with color that come from quite different directions. Colored objects and scenes, oil paints, watercolors, acrylics, etc., are manipulated, displayed, and photographed for aesthetic and expressive reasons, and this is the domain of the artist, whether professional or amateur.

Last but not least, there are the scientists whose interest is mainly in getting at the mechanisms of color vision. The motivation is common, but the approaches and researchers span a range of disciplines: physics, biology, chemistry, anatomy, psychology, engineering, and the medical sciences. Different puzzles and different aspects of this complex subject capture the specific interest of these different scientists, and the languages they speak are as diverse as their disciplines and the issues they discuss.

In a nutshell, the area of color and color vision is an extremely complex one, and one in which a serious scientist coming fresh to the field does not easily find sure footing along a clear path that will take him through difficult terrain already explored into the still unexplored territory ahead. In his volume on Human Color Perception Joseph J. Sheppard, Jr., observes that the relative newcomer to the subject is faced with an acute problem. "How is he to distinguish among established experimental fact, generally accepted theory, and disputed hypotheses? On the one hand he is faced with cyclopedic treatments of particular details of the visual process containing much more specific information than he initially requires. As an alternative he finds textbook style reviews typically containing brief summaries of experimental findings collected in

support of, or presented within the framework of, a particular theory of the visual mechanism. And he frequently finds conflicting theories or interpretations in different texts. None of these treatises alone satisfies his need for a short critical presentation of the minimum material necessary for a reasonably comprehensive view of the subject" (p. 1). Dr. Sheppard has consequently set about satisfying the need for himself by his own reading, and has published his own view of the subject as it emerged from this reading. It is, he says, a "critical study of the experimental foundation" (the book's subtitle) of human color perception written by a "relative newcomer" but yet addressed to "clinicians, engineers, and scientists who are interested in human color perception as an area for active research participation." Sheppard tells us in the preface that "The preparation of a book with the present title might imply that the author feels qualified to select the material necessary to cover the essentials of the subject" but he modestly adds "I disclaim any such expertise." What began as a collection of some published experimental results selected from the physics, physiology, and psychology of color vision, formed the basis for two study reports prepared for The RAND Corporation, which in turn formed the basis of the book. It "is intended to be a syllabus, presented through an ordered discussion of selected experimental results" (author's emphasis).

We believe that such a book could be extremely useful and a welcome addition to the already over-cluttered visual literature if it did well any or all of the following:

- A. Explain well, that is, clearly, consistently, and unambiguously, aspects of color that are difficult to assimilate and often misunderstood.
- B. Report in systematic fashion related facts and data that are scattered throughout the literature.
- C. Provide a thoughtful review of existing theory and/or an original theoretical development that is provocative and testable.

Unfortunately, the present reviewers have concluded, after a careful reading, that we would be unlikely to use Sheppard's volume as a syllabus in any of these three categories. This is a harsh judgment of a volume, and one that requires, to be at all fair, that we detail some of its major faults.

In his volume, Sheppard makes a strong attempt at the kind of explanatory function listed as (A) above with respect to the CIE system of color specification. This is an often misunderstood and misused numerical system of colorimetry that has been adopted as an international standard by the International Commission on Illumination (Commission Internationale d'Éclairage, abbr. CIE). The system is based on average data from color-mixture and matching experiments, and the original data have been mathematically transformed to

a system of units chosen primarily so as to be convenient and useful to both colorimetrists and photometrists. The system enables one to convert distributions of radiant energies in the visible region of the spectrum, measured by physical instruments, to light units, and also to three-valued numerical specifications of their colorimetric properties. The colorimetric units specify identities and non-identities, that is, they can be used to examine any two physically different spectral energy distributions and, by the appropriate computations, determine whether or not the two lights in question would appear identical (metamers) or not (non-metamers) in a standard color-matching situation to an average (in CIE terms, "Standard") observer. It is common practice also to express the three numerical values ( $X$ ,  $Y$ ,  $Z$ ) in percentage units ( $x$ ,  $y$ ,  $z$ ) and display the values graphically in a two-dimensional ( $x$ ,  $y$ ) coordinate system known as the CIE chromaticity chart. This chart conventionally includes a plot of the spectrum locus for narrow bands of spectral energies, and it is here that misuse of the system typically begins. The CIE system of colorimetric specification is, as we said above, based on color-matching data mathematically transformed to an arbitrary set of units, and it is intended to specify, by physical measurement and arithmetic computation, metamerism (color identity) or non-metamerism (color non-identities). As such, the system is of great value, both to experimental scientists and in various color technologies. It does not specify what any identical colors look like (that is, whether they are red, white, pale green, and so on) nor does it specify how different two different colors will appear (the numerical difference in CIE chromaticity values is not simply related to perceived color difference, nor are the numerical differences comparable in magnitude from one pair of chromaticities to another). But most scientists and engineers who are familiar with the visible spectrum know, or think they know, or think they know for "standard viewing conditions," or think they know for "standard viewing conditions" and the "Standard Observer" and a "standard level of luminance," what hues are associated with the different wavelengths of the spectrum. The spectrum locus on the CIE chromaticity chart begins to take on hue labels, near-by loci take on similar labels, the center of the diagram farthest from the spectrum locus begins to "look white," and the confusion, misunderstanding, and misuse of the system is in full bloom.

Sheppard spends many pages describing the CIE system correctly, and emphasizes that "CIE specifications indicate metamerism, and say nothing about appearance" (p. 35). One suspects, however, that he doesn't quite believe his own statement, for in any event he will certainly manage to unconvince the unguarded reader by his reproduction of Kelly's CIE chart in which different sections are labeled with hue names, and by his reproduction as the frontispiece for his book the Louis M. Condamine oil painting of these hues on the same chromaticity chart! And although the reader is warned that doing this "is fraught with

danger," Sheppard tells him that "it is quite useful, for many purposes, to associate with a given CIE specification a fixed 'appearance' as 'perceived' by the Standard Observer" (p. 35).

The author's own apparent confusion about this issue shows up most clearly in the context of data concerned with phenomena of color constancy, the tendency for objects to retain approximately the same color appearance under different (e.g., daylight and incandescent) illuminations. Here (pp. 105-107), Sheppard seems to be putting forth the view that the CIE system somehow represents what appearances the "Standard Observer" sees, but that it does not represent what "a normal real observer would perceive" (author's italics) because the "Standard Observer" is limited to standard viewing conditions, unlike the "real observer" whose visual system adapts as he moves from daylight to indoor illumination. Thus he discusses the constancy and adaptation phenomena in terms of the CIE chromaticity chart, with "a long vector" to represent a large "blue-yellow" shift (presumably for the Standard Observer), and a short vector that represents "the actual small change in appearance." Whether or not the author himself is clear about the relation of adaptation to perceptual constancies, his exposition of this issue in the context of the chromaticity diagram is one from which we would steer away our own students.

A related issue, also concerned with maintaining a clear distinction between perceptual attributes of visual sensation and systems of units that specify visual equivalences, comes up in the context of photometric light units as differentiated from perceived brightnesses. Here, when radiant energies have been evaluated, in visual experiments, with respect to their capacity to evoke light sensations, whether minimal light sensations in threshold experiments or equally bright light sensations in matching or flicker experiments, the data can be used to convert measured radiant energies to a system of photometric light units (foot-candles of illumination, millilamberts of luminance, and so on). In fact, the photometric evaluation of radiant energy is incorporated as one of the values of the CIE system of colorimetry, as we mentioned earlier. Like the three-valued colorimetric specifications, specification of the light values of radiant energies in photometric units is extremely valuable to visual scientists and in various technologies.

The photometric units can tell us when two different spectral distributions of radiant energy will be equally bright under comparable viewing conditions. They can not tell us whether a light having, say, a photometric luminance of 2 millilamberts will look 2 times, 4 times or 1.1 times as bright as another light whose photometric luminance is only 1 millilambert. The visual literature is replete with data from perceptual-scaling experiments designed to determine just what the relation between light units and perceived brightness magnitude is for a variety of viewing conditions. The visual literature also abounds in careless interpretation of

photometric units as if they could be used directly to describe relative magnitudes of perceived brightness. The Sheppard volume simply adds another instance to this unfortunate state of affairs. An example occurs in Sheppard's discussion of flicker phenomena. It is known that the uniform brightness that results from the fusion of rapidly alternating light stimuli of different intensities is identical with that which would accompany the same average flow of light energy in continuous form (Talbot-Plateau Law), and it is also known that light stimuli alternated at certain rates slower than the fusion frequency do not follow this same law, but look brighter than a continuous source of the same average photometric luminance (Brücke-Bartley Effect). Sheppard (p. 147) employs a graphical description of these facts in which the ordinate is labeled "level of brightness sensation" and which he discusses in terms of perceived brightness ("... at 10 cps the intermittent stimulus evokes twice the brightness with half as much energy"), but in which he also represents the "steady stimulus level" and the "Talbot-Plateau" level at ordinate values which can only be interpreted as photometric luminance units, and not scaled units of perceived brightness.

Once again, a clear and consistent presentation of the issue, keeping photometric stimulus measures and perceived brightness magnitudes distinct, as they in fact are, would serve a useful didactic function, but Sheppard's treatment fails of this objective.

A second useful function that we have said such a volume might serve is to report in systematic fashion facts and data that are scattered throughout the literature. Sheppard has stated this as one of his own specific purposes.

Chapter IV of the volume, "Retinal Sensitivity," does indeed collect, in one place, data on spectral sensitivity functions obtained by a variety of methods and for different stimulating conditions (field sizes, retinal locus, and so on), that have been reported in a variety of journals over a span of many years. This collection of data is good to have, although even here one might question the grounds for their selection. A paper of our own is cited, for example, in connection with irregularities in the spectral sensitivity function, some of which we interpreted as evidence only of observer variability and some of which were statistically significant features. Sheppard ignores, however, the main finding of the same paper showing that there is a slight Purkinje shift in a 1° foveal area with change from light to dark-adaptation when citing evidence on the issue of possible rod influence in foveal areas of comparable size.

And when he comes to discuss the influence of chromatic adaptation on the spectral sensitivity curve (also called luminosity function and luminous efficiency function), it is hard to know what the reader will be left with. "Finally, it is important to note," writes Sheppard, "that the relative luminous function  $V_{\lambda}$  does not

seem to be affected by the adaptation phenomena, even after an intense color adaptation that would seem to reduce necessarily the sensitivity in the region of the adapting color" (p. 109). This statement is simply false, and we could cite numerous experiments in documentation. One of our own publications in 1954 summarized our experimental exploration of the issue as follows: "The results of the series of experiments reported here confirm the generality of the experimental finding that the form of the photopic foveal luminosity function is dependent upon the state of chromatic adaptation", (pp. 220-221). But what is really puzzling is that Sheppard, despite his first statement reported above, seems to know at least this publication, for he also writes "Hurvich and Jameson . . . found for one subject no change whatever in the shape of the subject's relative luminosity function for yellow adaptation, while changes for red, green, and blue adaptation were appreciable" (p. 113). This is not the kind of systematic and accurate reporting of facts that is needed.

Chapter VII features a section called the "yellow anomaly." We are frankly unable to summarize this, but since Sheppard himself writes (p. 113) that "the data seem incapable of supporting a definitive statement either of the exact nature of the 'yellow anomaly' or of its physiological origin," further comment seems superfluous. There is also a strange and equally baffling section entitled the "white anomaly." The word "white" is given two meanings. One appears to relate to characteristics of an object or a surface, the other denotes "chromatic neutrality, or achromacy." "The first meaning of 'white' . . . states that white is a sensation whose presence or absence may be simply reported by an observer. The second meaning is less clear, and it is difficult to make the meaning more precise. Therein lies the 'white anomaly'!" (p. 114).

In this same context, some of our own studies are cited to show that, to determine whether something will look white, one must specify the spectral distribution of the radiant energy, luminance level, stimulus area, stimulus duration, and the observer's adaptive state. This statement, which is true, represents nothing anomalous about perception of whiteness, but a general fact about all color perceptions. They all, whether we are concerned with white, red, yellow, green, or blue, depend on the stimulus parameters listed above and on the state of the observer's visual system. But Sheppard seems not to have assimilated this basic fact of perception, for he adds "This represents a far more detailed specification requirement than that for, say, a 'red' " (p. 114). And this statement is made despite his discussion on p. 9 which is concerned with the variety of conditions that affect perceived color, and in which he used "red" as the specific example.

With respect to the third potential contribution of a volume of this sort (C, above) Sheppard points out in his introduction that "the present study . . . differs sharply from most discussions of human color perception in that no specific attention is given to the details

of extant theories of the visual mechanism" (p. 4), and he provides the reader with a selection of references for summary reviews of color theory. Throughout the book, however, issues related to theories of the visual mechanism do, of course, arise, and Sheppard makes it clear that he finds all extant theories wanting. The crux of Sheppard's questioning seems to concern the prevailing notion that photopic, color vision depends on the existence, in the retina, of three different cone photopigments that have different selective spectral absorptions. Although he accepts the pigment, rhodopsin, as the visual pigment of the retinal rod-type receptors and as demonstrably related to scotopic vision, he is unwilling to accept the conventional view that the three-variable nature of photopic color vision rests, most peripherally, on the different absorption characteristics of three different cone receptor pigments. His collection of individual photopic retinal sensitivity, or luminosity, functions is marshalled as evidence that one cannot see the operation of three selective photopigments in terms of consistent sub-maxima or humps in these spectral sensitivity curves. In Chapter V, he points with suspicion to the fact that it has not been possible to extract primate cone pigments in the way that their rod pigments have been extracted and studied in solution, even though the presumed densities of pigments in individual cone elements should be approximately as high as the rhodopsin density in individual rods. Here, he seems to have missed an important difficulty for the study of primate cone pigments in solution. The difficulty to be surmounted is not so much a matter of pigment density per individual element, but rather one of the relatively large total number of rods and small total population of cones in the whole duplex retina which goes into the retinal extract of primates.

In recent years, however, a major advance has occurred in this area which has made it possible to study, by microspectrophotometry, the absorption characteristics of single retinal receptor cells. By these relatively new techniques, the existence of three different cone pigments has been demonstrated in the goldfish retina, in monkey retinas, and in the human retina. Sheppard is aware of these data, but argues that the sample of absorption data for individual primate cones is not yet large enough. We are in complete agreement here that, particularly for the human retina, more data for a larger sample of cones are needed if we are to know with reasonable precision and reliability, the spectral distributions of the human cone absorptions. But we do not question the validity of the measures published so far or that they will ultimately fall into place in a larger sample of comparable measures. Sheppard, on the other hand, recognizes the validity of the three photopigments found in a large sample of goldfish cones, but remarks that "one must remember Gordon Walls' conclusion of twenty years ago, recently echoed by DeValois, that there is good evidence that color vision systems have evolved several separate times -- once in insects; again in fish, reptiles, and birds; and still again in primates. It would thus be little

more than a coincidence if the details of the visual systems in man and fish were the same" (p. 67). One detail in which it is definitely predictable that man and goldfish will differ is in the precise wavelengths of the absorption maxima of the visual pigments in the two different retinas. The goldfish pigment system is based on retinene, and vitamin A., rather than the retinene, vitamin A, system of marine fish and of primates, and the rod pigment absorption of goldfish peaks at a longer wavelength (about 525 nm) than the rod rhodopsin in man (about 500 nm). Sheppard, however, neither mentions this nor does he seem to be aware of it, for he argues that "the data for the primate cones so far examined do not follow the pattern exhibited by the goldfish results" (p. 66). The goldfish have a cone with maximal absorption at 625 nm. This, Sheppard calls a Young-Helmholtz type red receptor, but he points out, no absorption with a peak in this region is found in the primate cones. The argument is absurd in view of the known differences between pigment systems in fresh water fish and primates. As for the wavelength peak of a "Young-Helmholtz type red receptor," Helmholtz himself, in 1896, derived this so-called "fundamental" as a doublehumped function with a long wave maximum in the 580-590 nm region of the spectrum'. The specific peak wavelength requirement of this theory seems to be Sheppard's own.

What original contribution does the author present as a viable alternative to the prevailing concept of three cone photopigments as the receptor basis for human color vision? He does not rule out the possibility that the prevailing concept may be correct, but mentions spectrally selective waveguide effects that could vary with cone physical characteristics, independently of, or in addition to, visual pigment differences in different cones. He uses Polyak's anatomy of the retina to argue that each foveal cone is connected to three bipolar cells. And in some way it is three bipolars connected to a single cone that gives the three-variable system rather than the three different cones that most people assume. As for the waveguide properties, he cites Enoch's studies and says that although his results are difficult to interpret, "there is evidence of spatial spectral separation within a single receptor outer segment" (p. 79).

Had Sheppard picked up this notion and gone on to develop a model showing how a single cone, by means of waveguide effects, could stimulate different responses in three different bipolar cells, this model might have proved wrong but at least it might have been challenging. He does not do this, but rather, shifts the discussion to metabolic differences between rods and cones shown by effects of drugs on the electroretinogram.

Thus the reader is left, not with a testable model, but with a "cumulative implication" that the "peripheral mechanism subserving human color vision is not based simply on three cone photopigments, but rather is based on a combination of variation in cone physical

characteristics (including any pigments) and multiple bipolar analyses" (p. 157). And among his recommendations with respect to a program for future research, Sheppard pays homage to the time-honored cliché, "It is the author's belief that perhaps the surest road to success in this field lies in a concentrated program involving a group of subjects from birth to death" (Author's ital., p. 160).

What prompts a novice to undertake such a volume? The question is broader than the book reviewed here, for, hardcover books aside, the journals keep cropping up with "new" discoveries of old phenomena, which lead, in turn, to new "theories" of the visual mechanism to account for the "new" discoveries. What is there about the area of color vision that leads to this state of affairs? There is, of course, the fact that the phenomena are largely in the public domain; colored visual effects are readily available via colored papers, filters, pigments, photography, and now television. But this is a superficial answer, at best, and addresses itself to only part of the question. In the last analysis there is something about the state of the field.

The crux of the matter may well be that in the area of color vision we have had two competing "paradigms" for a century or more and that therein lies the source of the continued state of confusion to which Sheppard's book will add its share. We say this because we agree with the view expressed by Thomas Kuhn in The Structure of Scientific Revolutions that "normal science" means research firmly based upon one or more past scientific achievements, achievements that some particular scientific community acknowledges for a time as supplying the foundation for its further practice". The textbooks and famous classics of science that "expound the body of accepted theory," says Kuhn, serve "for a time implicitly to define the legitimate problems and methods of a research field for succeeding generations of practitioners." When a given paradigm that defines "normal science" fails to function adequately, after some competition and struggle it is replaced by another paradigm with a different view of nature, and this is the way scientific development proceeds.

But in the science of vision, for more than a hundred years now, the views of two giants -- Helmholtz and Hering -- have continued to compete in seemingly irreconcilable and interminable disagreement on fundamental aspects of the visual mechanism and its functioning. Helmholtz's orientation was associationist and empiricist, and for him, many perceptual problems were matters of mental interpretation and inference. Hering, on the other hand, sought to account for the phenomena of interest, including the "learning" aspects of the varied perceptual problems, in terms of physiological mechanisms. Their different orientations led them to treat problems of binocular vision and space perception in very different ways, and their different orientations also found expression in their specific views of the color vision mechanism.

Although Helmholtz in 1852 had rejected Young's "three-color" analysis of 1802, he later modified his position and so strongly sponsored Young's views that the theory is usually known by the name "Young-Helmholtz". In its classical and most parsimonious form, the Young-Helmholtz three-component theory is simple. In addition to the rods, which subserve twilight vision, the eye contains three kinds of cone photoreceptors. Each type of cone contains a differently selective photochemical substance with absorption maxima at different points in the spectrum. Each cone is in turn associated with its own specific nerve fiber system and is simply correlated with one of three specific fundamental color sensations, namely, red, green, and blue (or violet). All visual sensations are considered as compounded of varying amounts of these three excitatory systems and their associated sensory qualities. Black is the condition of zero excitation, and white arises from equality of all three color sensations. Yellow presumably emerges as a new hue quality from equal red and green excitations and sensations.

The Hering theory conceives the three-variable visual system to function in a fundamentally different way. The three neural variables of the color vision system are three pairs of physiological processes that are directly associated with three pairs of unique sensory qualities. The two members of each of the three pairs are opponent. That is, the paired physiological processes are assumed to be opposite and antagonistic in nature and the paired sensory qualities (red-green, yellow-blue and white-black) are also mutually exclusive. Hence, the assumption that the blue and yellow physiological events are opponent or antagonistic accounts for the fact that the sensory response can be either blue or yellow but not both at the same time in the same place. The same is true of the red-green system, hence we have no sensations that can be properly described as greenish-red or reddish-green. Non-opponent individual members of the different pairs can coexist so that we see red-blues, green-blues, blue-greens, yellow-greens, and yellow-reds. The white-black system in this schema is also an opponent one, and mid-gray is not an additive combination of white and black but represents rather the equilibrated intrinsic basal-activity sensation that is associated with the equilibrated condition of the three paired physiological processes.

The Helmholtz theory appears to be the simpler of the two and has undoubtedly been the "most widely followed of visual theories" (c. p. 835). But the Hering position has also always had its adherents, and thus it has always also received considerable attention in textbook presentations. What is there about the field of color vision that has permitted the continued competition of two such fundamentally different views?

A large part of the answer to this intriguing question can be found in Y. Le Grand's excellent summary volume on Light, Color and Vision. After listing the various aspects of color vision for which every theory



of vision should ideally account, he points out that the facts and conditions are divided into two main subsets, and adds, importantly for our concern about competing paradigms, "According as the proposer of a theory inclines more to physics or to psychology, he places more emphasis on the one or the other of these groups of conditions" (7, p. 401). The physicists emphasize the data of color equivalence, the laws of color mixture and three-stimulus color matching, luminosity functions, and so on, and they tend to analyze their data in terms of the simpler Young-Helmholtz paradigm. And, as Le Grand points out, none of the issues involved in this subset of facts is concerned with color sensations, as such. On the other hand, "Hering and his followers," says Le Grand, "are more interested in the psychological evidence" (7, p. 402). In the subset of facts that Le Grand calls the "psychological evidence," he includes the hues and saturations evoked by narrow-band spectral radiations, the changes in these hues with change in radiant intensity for fixed wavelengths, the neutralization of hue in mixtures of spectral radiations, and the effects of adaptation: In short, the facts and laws of color appearance.

A similar view of the divided nature of the field, its practitioners, and its paradigms was expressed some years ago in a thoughtful review article by L. C. Thomson. Thomson considered the fact that the data of color-matching experiments with three mixture lights can be expressed mathematically in the form of three simple linear equations, and can thus be readily transformed to the hypothetical "three fundamental sensations" of the Young-Helmholtz theory. And he considered it understandable that "physicists, who by training appreciate easily a mathematical argument, are usually in favor of Young's hypothesis, and physiologists and others, whose mathematical knowledge is not so adequate, have been the originators of rival ideas. So impelling is the mathematical argument to some that they consider any other . . . as necessarily fallacious. For many years feelings have run high because of the unshakable dogmatism of those in support of Thomas Young" (8, p. 11). On the other hand, "Biologists, knowing that the number of variables operative is larger than the physicist has realized, thus become critical and often skeptical of the mathematical approach" (8, p. 12).

Kuhn has pointed out that what ultimately leads to the downfall of a given paradigm is that anomalies develop with which the paradigm cannot successfully cope. In the case of color vision theory, each group has pointed an accusing finger at the other, as indicated by the Thomson quote already given. But what is astounding to those who do not support the Young-Helmholtz theory of color vision is that, as Thomson says, "the hypothesis does not account for the appearance of the colours as seen" (8, p. 24). Nevertheless, in its defense, Thomson also writes: "In fairness to the Young-Helmholtz hypothesis in its modern form one must say that it does not attempt to explain the appearance of the sensations" (8, p. 25).

Although the theory "in its modern form" may not "attempt to explain the appearance" of colors, the theory was originally developed to do just that, and implicit in the thinking of many of its adherents is the conviction that it does, of course, do it adequately.

The spectral distribution curves of the three basic mechanisms that are still reproduced in many texts were originally drawn by Helmholtz to represent the degree of excitation of three fundamental color sensations, and the different color appearances evoked by different spectral stimuli were related to the relative degrees of excitation specified by the three basic sensation curves. Thus, light that "stimulates the red-sensitive fibres strongly and the two other kinds of fibres feebly" gives the "sensation red"; light that "stimulates the red-sensitive and green-sensitive fibres moderately and the violet-sensitive fibres feebly" gives the "sensation yellow," etc. (9, p. 144).

Helmholtz also followed through with this form of analysis for various types of color blindness. Thus "red blindness would be explained as a paralysis of the red-sensitive nerves" (9, p. 151); to such individuals the long wave portion of the spectrum would appear "as a saturated green of low luminosity" (italics in original), and that portion that looks yellow to normals would "appear as brilliant saturated green," (italics in original), and so on.

Another type of color blindness, he conjectured, would result from paralysis of the green sensitive nerves, and these individuals would see only reds and blues.

In fact, the attempt to state perceptual correlates for the types of "color-blindness" that Helmholtz was referring to has caused serious difficulty for the theory, particularly since evidence from the rare cases of color blindness in one eye with normal color vision in the other makes it quite clear that the defective eye sees yellow and blue hues and neither reds nor greens. Such evidence has called forth *ad hoc* hypotheses about the basis of color blindness as something other than the simple loss of one of the three basic systems of the theory.

Helmholtz also discussed after-image phenomena at length and treated problems of successive and simultaneous contrast. His views on these aspects of color appearance reflected his basic notions about the distinction between sensation v. perception, his emphasis on learning, and his concept of judgment and "unconscious inference" as crucial in the interpretive process by which sensory information is presumably transformed into conscious percept. His discussions of simultaneous color contrast provide good examples of the paradigm at work. Consider, for instance, the fact that a small piece of white paper looks lighter on a black background than on a white one, looks greenish against a red background, yellowish on a blue background, and so on. Helmholtz's explanation said, in essence, that the effect occurs because a mistaken

inference is made concerning the "real" color of the small white test object. Mistakes "may result from our custom of judging of local colour according to the brightness and colour of the objects seen at the same time. If these relations happen to be different from what is usual, contrast phenomena ensue" (<sup>10</sup>, p. 106). "When a particular colour is made dominant in the visual field, a paler shade of the same hue will look white to us, and real white will seem to be the complementary colour. Thus the idea of what we mean by white is altered in this case" (<sup>11</sup>, p. 274).

The explanation for object color contrast is reechoed for contrast colors seen in double shadows, when a white paper is illuminated by weak daylight as one source and candlelight, as another, and an opaque object is held so as to intercept part of the light from each source. As Helmholtz says: "Two shadows will be perceived. The one that would be there if the candle were absent may be called the daylight shadow; and the one which depends on the presence of the candle, the candle shadow. The daylight shadow is illuminated by red-yellow candle light, but not by daylight. It appears in its objective colouration, namely, red-yellow. The candle shadow is illuminated by white daylight, but not by the red-yellow candle light. And thus while it is objectively white, it appears blue or complementary to the colour of the ground, which is a pale red-yellow, since the unshaded portions of the paper are simultaneously lighted by the white daylight and the red-yellow candle light. The colourations are most distinct when the intensities of the two sources are so equalized that both shadows are equally dark" (<sup>12</sup>, p. 271).

"... in the experiment described above of coloured shadows thrown by daylight and candle-light, the doubly illuminated surface of the paper being the brightest object seen, gives a false criterion for white. Compared with it, the really white but less bright light of the shadow thrown by the candle looks blue" (<sup>13</sup>, p. 106).

Thus, in the Helmholtz paradigm, all such appearance effects are dependent on "cognitive" factors and, as Parsons (<sup>14</sup>, p. 231) has pointed out, no serious attempt was made to correlate such facts with the postulated physiological mechanisms of the three-color theory. This kind of "dual" treatment of color phenomena is in sharp contrast to the Hering paradigm, in which contrast effects are subsumed as another manifestation of the opposite nature of the paired color processes and are explained on the hypothesis that neural activities associated with any region of retinal stimulation are not independent of activities in other regions, but related to them in mutually opponent (in present-day terminology, "excitatory-inhibitory") fashion. Thus, redness activity in one area induces the opposite, greenness activity in adjacent areas, and so on, so that the piece of white paper when viewed against a red background looks greenish because that process has actually been activated in that region of the retinal tissue, and so on for the other background contrast effects. Similarly, in the colored shadow situation, the

blue-green appearance of the shadow illuminated only by daylight is actually associated with blue- and green-coded physiological processes induced by the adjacent yellow and red activities stimulated by the intermixture of candlelight with the daylight in the non-shadowed areas. This kind of physiologically based account of color contrast, which is inherent to the Hering paradigm, is appealing to many students of color vision, but to many it is a weak advantage in the face of what Thomson called the "impelling mathematical argument."

In fact, there is a major irony in this "mathematical argument" and its influence on theoretical biases throughout the years. The Hering view, which we have consistently referred to as the opponent-process theory, has more typically been called, especially in the older textbooks, the "four-color" or "tetrachromatic" theory, in distinction to the "three-color" or "trichromatic" one. The labeling results from a concern with only the chromatic processes, paired red and green and paired yellow and blue in the Hering paradigm, and independent red, green, and blue (or violet) in the Young-Helmholtz schema. By omitting the black-white pair of physiological processes and its associated visual qualities, we lose sight of the fact that the Hering schema is a system of three paired variables. And unfortunately some of Hering's own supporters were among those guilty of muddying the waters, and gave the mathematically-minded physicist the ammunition with which their own positions could be bombarded.

The issue of three versus four independent mathematical variables on which so much paper, ink, and time has been wasted need never have been debated for a moment. Although the two theories are fundamentally and conceptually at odds, each rests on three independent variables, in the mathematical sense. Hering (1878) made it quite clear that the assumed physiological basis of his own theory was a three-dimensional one<sup>15</sup>, and in the 2nd edition of his volume on Physiological Optics (1896) Helmholtz not only recognized Hering's theory to be a three-variable schema, he even wrote out three linear transformation equations that relate the Hering paired (+, -) variables to his own set of three all-positive ones<sup>16</sup>. The regrettable development of the illusory mathematical issue into a matter for controversy can be ascribed, at least in part, to an accident of scholarship. Helmholtz's treatment of Hering's opponent process theory as a "three-variable" system is very little known, as are his later quantitative developments of his own theoretical schema. This 2nd edition material was lost to much of the scientific community when, after his death, Helmholtz's former students, v. Kries, Nagel, and Gullstrand, assumed responsibility for publishing a third edition of the famous treatise (1909-1910). They thought more highly of the first (1866) than the second (1896) edition, and used it as the basis for a third, supplemented by their own chapters to bring the material up to date. This 3rd edition -- the revamped 1st -- was translated into English and published by the Optical Society of America

in 1924-1925, and it has recently been reprinted by Dover Press. Helmholtz's own later treatment of the color vision problem remains largely buried in the untranslated second German edition.

The last decade or so has finally witnessed a more or less generally understood clarification of the "numbers" issue in the two competing paradigms. Active researchers in the field at least, albeit often unaware of Helmholtz's mathematical treatment, have had their attention directed to the fact that such simple mathematical relations between the three unimodal variables of the one scheme and the three paired variables of the other have been offered by Schrödinger (1925), E. Q. Adams (1923), and D. B. Judd (1949)<sup>6</sup>.

The reviewers were able to demonstrate that when the spectral response functions that correspond to the opponent process hypothesis are measured directly in a psychophysical experiment, the same functions also account quantitatively for the "three-primary" spectral color matching results, as well as for a variety of other equivalence, discrimination, and color appearance data<sup>7</sup>. And other analyses of quantitative measures have been made on the basis of opponent-process models by, for example, Boynton<sup>8</sup>, Guth<sup>9</sup> and Walraven<sup>10</sup>. Thus, Le Grand's dichotomy has become increasingly less valid, in the sense that it implies that supporters of the Hering view do not handle the quantitative measures of color equivalence but concentrate only on the appearance data. The two paradigms are no longer validly distinguished in terms of mathematical precision and quantification per se.

Another important development has occurred during the same period that relates to the relative "acceptability" of the physiological assumptions of the two paradigms. Helmholtz's notion of "red-sensitive," "green-sensitive" and "violet-sensitive" nerve fibers was one that seemed perfectly reasonable to generations of biologists and neurophysiologists. To Hering, one of whose major interests was in the mechanisms of biological adaptation and biological equilibria, the visual system was a prime example of the operation of antagonistic neural processes, analogous to the opposite processes of general metabolic activity characterized as "assimilation" (anabolism) and "dissimilation" (catabolism). The opponent visual processes were manifestations of basic, reciprocally related, neurochemical changes, and Hering's theorizing was tied to the interplay of these reciprocal mechanisms both in time and across spatially interconnected elements of the neural tissue.

But these views were not readily assimilable into the prevalent paradigm of neural activity, and they tended to be rejected as physiologically implausible. Any number of such negative judgments can be cited, but they are epitomized by Selig Hecht's statement: "Hering's ideas of assimilation and dissimilation mean nothing in the modern physiology of sense organs and nerves"<sup>11</sup>.

Following Hartline's discovery, however, that mammalian nerve can respond to stimulation by "on," "off," or "on and off" discharges<sup>12</sup>, the neurophysiologists began to change their views about neural response as either unimodal excitation or "silence," and Granit, in particular, went on to establish that the on- and off-responses were manifestations of true physiological antagonism in the neural processes. In 1955, Granit described his findings as a "belated vindication of the essential truth of Hering's contention that there are two fundamental processes of opposite character in the retina"<sup>13</sup>.

Granit saw the relevance of the opposite neural processes to the visual coding problem insofar as it concerned phenomena of black-white contrast. Unfortunately, he did not, at the time, look for a comparable hue coding in connection with selective "on" or "off" responses to different wavelengths.

It was only when Svaetichin demonstrated (1956) that individual cells in the fish retina show graded d.c. potential changes that reverse in polarity with change in stimulus wavelength,<sup>14</sup> and after his findings had been confirmed and accepted, that electrophysiologists were alerted to the correlated phenomena of wavelength dependent "on" or "off" spike discharge. But since that time there has been a growing accumulation of published records that show unit nerve cell firing at light onset to short wavelengths, and suppression of spontaneous activity during stimulation with "off" discharges to long wavelengths, or vice versa<sup>15</sup>. The records are from single cells in the retina and optic tectum of goldfish, optic nerve fibers of the ground squirrel, lateral geniculate and cortex of primates. And the records from single cells also show that they are influenced, not only by stimulation of single retinal "points," but by relatively large "receptive fields" which are often organized spatially in concentric center-surround, excitatory-inhibitory, opponent relations. The microelectrode recordings provide a picture of the visual response system that is both complex and far from "filled in," and we are not yet ready to decipher the neural "color code" with any certainty, but it is obvious that the code involves an opponent (on-off, excitation-inhibition, + -) basis of neural organization and response.

It was shortly after we had published our psychophysical measures of the opponent color responses and Svaetichin's recordings of wavelength-dependent cellular polarity reversals had appeared in the literature, that another development occurred in the area of color vision that shook the physicists' faith in their "mathematical argument." This time, the jolt came in the form of a "threat" that the color vision system might, despite all the trichromatic evidence, operate by means of only two variables rather than three, and once again, the turmoil was based on misunderstanding or simply lack of insight about the phenomena that underlay all the excitement.

The development we are discussing was Edwin Land's demonstration that a variety of hues can be perceived in superimposed images formed by two projected "black and white" transparencies, when a colored filter is placed in front of one projector and either a different colored filter or no filter at all is used with the second projector". When the "full-color" effects of these two-color projections were first publicly demonstrated, they were reported with an unprecedented fanfare of publicity in newspapers, magazines, and scientific journals. *Fortune's* article entitled "An Astonishing New Theory of Color Vision" featured the challenge: "Remarkable discoveries by Edwin Land of Polaroid show that scientists since Newton have been completely fooled about the way the eye sees color"<sup>14</sup>. And a large enough number of those who saw Land's demonstrations at meetings of professional societies -- photographers, engineers, biophysicists, psychologists, etc., were struck by the seeming magic of his effects that it was difficult for the minority who saw these demonstrations as "stunning illustrations" of well-known visual phenomena even to get a hearing. Just what had Land "discovered"?

It is reported that Land first saw his effects for himself in the course of laboratory explorations of additive three-color photography that he was conducting in connection with his interest in developing a one-minute color process of the sort that he had already perfected and marketed for black-and-white photography. For his laboratory projections he was using transparencies made by the conventional color-separation technique of taking separate photographs on black-and-white film through each of three colored filters (a red, a green, and a blue). The resulting transparencies thus have different density distributions that depend on the spectral transmissions of the colored filters and the spectral reflectances of the colored objects that are photographed. The three black and white transparencies are then carefully registered for projection, respectively, through appropriate red, green, and blue filters, and a conventional three-color additive photograph results that mimics, in essence, the colors of the original scene.

If one were thinking in terms of the simple Young-Helmholtz paradigm of three fundamental sensations that are preferentially excited by light from three different regions of the spectrum, one would expect the blues in the scene to disappear when the blue filter was accidentally removed from in front of the "blue record" projector. Puzzlement about the fact that this did not happen was reportedly what brought Dr. Land back to the laboratory in the dead of night to see how much more "color information" could be eliminated from the projection and still preserve a "full" array of color hues on the screen. It was apparently at this time that Land had his own first demonstration of full color photographs with only two color separation records and a single color filter used in the projection.

As we pointed out earlier in this essay, the laws of

three-stimulus color mixture were at the core of the "mathematical argument" that caused physicists to favor the Young-Helmholtz paradigm. And even though it may be true, as Thomson said in 1953, that in its modern form the hypothesis does not attempt to explain the appearance of color sensations, it could only be because it is implicitly assumed that it does predict color appearance that Land could have declared that "color is not at all the classical function of wavelength and relative energy"<sup>15</sup> (p. 125), that the "classical laws of color mixing conceal great basic laws of color vision"<sup>16</sup> (p. 115), and that the "eye will see color in situations entirely unpredictable on the basis of older hypotheses"<sup>17</sup> (p. 116). Land himself did not propose a "two color" theory to supplant the old "three color" one. He did propose a two-variable coordinate system about which he wrote: "We feel that these experimental results require the kind of coordinate system we have used in order to correlate, predict, and understand"<sup>18</sup> (p. 268). The coordinate system is based on the light transmissions of the two transparencies, one recorded with a short wave transmitting filter, the other with a longer wave one, in corresponding image areas. The two coordinates represent percentage of available short wavelength stimulus on the abscissa and percentage of available long wavelength stimulus on the ordinate, and the "color at a point in an image depends on a ratio of ratios; namely, as numerator, the amount of a long-wave stimulus at a point as compared with the amount that might be there; and, as denominator, the amount of a shorter wave stimulus at that point as compared with the amount that might be there"<sup>19</sup> (p. 636). In this system, those values that are greater for the longer wave stimulus than for the shorter one are seen as reds, oranges and yellows in the projected image, whereas those that are less for the longer wave stimulus are seen as complementary green and blue hues. Along the diagonal, where the percentage values are equal in the two records, the corresponding areas of the projected image are approximately achromatic, i.e., white, gray, or black.

Land's coordinate system can be comprehended most readily with reference to the simplest stimulus situation of the general class with which he is dealing. This is the double colored shadow case described before in the quotation from Helmholtz. We may consider the daylight illuminant as the short-wave record projector, the candlelight as the longer wave source. The shadow that is cast on one part of the projection screen by partial interception of the daylight source would be an image area having a small percentage of the available short-wave stimulus and a maximal amount of the available long-wave (candlelight) stimulus. Thus, this shadow area plots in the coordinate system above the diagonal where reds and yellows are seen. The shadow cast on another part of the screen by partial interception of the candlelight beam would be an image area having a small percentage of the available long-wave stimulus and the full amount of the available, short-wave, daylight. Thus, it plots in the area below the diagonal seen in the complementary green and blue



hues. The part of the screen receiving full illumination from both the daylight and candlelight sources would plot along the achromatic diagonal at the 100 per cent locus seen as white. One can, of course, vary the depth of the shadows cast in this situation, and, by this means, the shadow colors seen can be systematically altered through a subtle series of hues and saturations. One can also readily develop the double colored shadow situation into progressively more complex patterns of multiple shadows by interposing additional shadow casters, and vary the depth of the shadows either by manipulating the positions of opaque objects relative to the two light beams or by varying the density of partly transparent objects. Thus, it becomes easy to imagine the progressive build-up of a complex, varicolored image pattern or shadow picture by starting from the simplest case of the double shadow. And slide projections of transparencies that have different densities in the different image areas are, of course, precisely such shadow pictures.

If Land's multiplex colored shadows are phenomena of the same class as the daylight-candlelight double colored shadows of the ancients, why were they not immediately recognized as color contrast effects rather than interpreted as requiring "an astonishing new theory of color vision"? In our own review of the color vision literature in 1960, we wrote, "The demonstrations by Land of 'full color' photographic projections using additive mixtures of only two chromatic sources or of one chromatic illuminant plus white that have aroused so much public attention are neither more nor less than stunning illustrations of simultaneous induction or contrast mechanisms"<sup>24</sup>. And among others who pointed out both earlier use of two-color photography and the relation of the phenomena to well-known visual effects, we may cite Gordon Walls<sup>25</sup>, D. B. Judd<sup>26</sup>, and Wilson and Brocklebank<sup>27</sup>. Land himself recognized very soon after his own personal discovery that the two-color projection technique that he was using had antecedents, and his papers contain references to some of these. Not widely noticed in the same Scientific American issue of 1959 in which Land presented an account of his findings<sup>28</sup>, was the "50 and 100 years ago" column in the front of the magazine, which contained a summary of an article published in May 1909 that began: "George Albert Smith and Charles Urban have exhibited very satisfactory moving pictures in approximately natural hues, using only two colors, with the aid of colored lighting projection."

But novelty of technique aside, the impact of Land's demonstrations was in their significance for the way the visual system operates. For one of the two competing paradigms, Land was correct in asserting that "it has become an article of faith in standard theory that the color seen at any point in a field of view depends on what wavelengths are issuing from that point and upon their relative strengths or intensities"<sup>29</sup>, p. 87) (reviewers' ital.). In the context of the same theoretical paradigm, contrast effects run counter to this "article of faith." As we saw above they were, in

Helmholtz's opinion, to be accounted for as "judgmental errors," "illusions of judgment," thus as effects not intrinsic to the visual system per se; but rather as reflections of the cognitive processes that consciously or unconsciously "interpret" the visual input. And, although it is fairly easy to follow the line of "unconscious inference" that might produce the commonplace laboratory demonstrations of contrast colors in, say, "gray" chips placed on different colored backgrounds, interpretive mechanisms postulated to explain the colors in complex image arrays are apt to take on rather implausible properties. As an illustration, we might take the account of these effects by Sheppard, whose book is the occasion for this essay.

Sheppard divides Land's demonstrations into two classes. One class, where the projection lights are very different in color, is to be accounted for by chromatic adaptation. The second, where the projection lights differ only slightly in wavelength, he calls the "pure Land Effect" (<sup>1</sup>, p. 127). This "pure Land Effect" implies to Sheppard "that the central mechanisms can 'unconsciously recognize' the external luminosity function with its neutral (i.e., white or achromatic) midpoint and use it to 'decode' the information in the projected scene" (<sup>1</sup>, p. 127). What the author is suggesting is that there is a brightness-wavelength correlation established by the luminosity function for an equal energy spectrum, and that the visual system uses the "near-Gaussian distribution in brightness sensations" to decode brightness to wavelength. With appropriately made photographs, "the cerebral mechanisms 'recognize' this familiar code and employ it to produce sensations in accord with experience. The only required chromatic content in the projected scene is that the two projection hues be discriminable so that the two 'halves' of the visible spectrum are differentiated" (<sup>1</sup>, p. 126) (Author's ital.).

Sheppard's appeal to chromatic adaptation to account for all but "the pure Land-Effect" echoes the explanation most frequently offered within the Young-Helmholtz, point-for-point, stimulus-response paradigm. D. B. Judd's sober appraisal published in JOSA in 1960 is a good example<sup>30</sup>. In this paper, Judd showed that a quantitative account of two-color projection effects could be based on formulas that he had worked out much earlier with H. Helson to describe the results of their experiments on chromatic adaptation. Since Judd also recognized that similar effects occur with instantaneous light exposures that hardly leave time for selective bleaching or sensitivity changes to influence the perceived colors, he also introduced Helmholtz's cognitive mechanism of "discounting the illuminant color" which presumably operates when viewing any "detailed scene depicting several three-dimensional objects." Under these circumstances, says Judd, "virtually the only possible perception corresponds to the object mode keyed to whatever illuminant-color perception is generated by the scene" (<sup>30</sup>, p. 260). But the perceived color contrast effects do not require that the scene represent three-dimensional objects that

"generate" a particular "illuminant-color perception." Unfamiliar geometric (flat) patterns serve just as well", and Land's demonstration of a head-on view of the outstretched American flag, arranged to appear in the "wrong" colors in a very brief flash exposure, is no less colorful than the appropriately projected flag that might be argued to evoke all of the appropriate unconscious inferences.

Thus, color contrast effects can be demonstrated under conditions such that they cannot be accounted for by selective chromatic adaptation (in 1893, Mayer<sup>2</sup> reported "vivid contrast colors" with spark discharge illumination lasting less than one-millionth of a second), and such that there is no plausible basis for associationistic interpretation based on accumulated visual experience. It would seem, therefore, that further progress in the analysis of such effects is more likely to result within the opponent-process paradigm which views the retina and associated neural cells as a tissue of functionally interrelated elements whose activities interact spatially in a mutually antagonistic fashion.

Land, himself, has reached the stage of proposing spatially related tissue systems that are subdivided into three retinal-cerebral mechanisms which he has dubbed "retinex"<sup>3</sup>. To our knowledge of his published work, though, he does not yet conceptualize these systems as related by mutual and opponent spatial interactions, but their properties seem to resemble more those of three-layered color film with independent photographic development of each layer to keep the three separate image densities "balanced" despite selective differences in their light exposures. How such compensatory adjustments might be made in a physiological system, except by the selective sensitivity changes of chromatic adaptation which Land has rejected<sup>4</sup>, is not clear. On the other hand, the physiological plausibility of mutually antagonistic interactions of activities within each of three paired opponent-color processes has been demonstrated by recordings of neural unit activities upon stimulation of the retina at various locations within the unit's receptive field. Excitatory-inhibitory response organization is, as we mentioned earlier, a commonplace finding in such records, even though we are still far from knowing the details of such organization as they change from retinal ganglion cells through units in the lateral geniculate to those in the visual cortex. Thus, it is not possible to generalize the neuro-electrical manifestations of these "color-coded" physiological interactions in precise systems of mathematical equations in the way that Hartline, Ratliff, and their co-workers have done for the retinal activities of the horse-shoe crab that seem to code phenomena that we perceive as brightness contrast<sup>5</sup>. We have, however, developed such a system of simultaneous equations that incorporate opponent interactions to describe measured results of perceptual color and brightness contrast experiments in intact humans<sup>6</sup>. These equations simply state, in more precise form, that, say, redness activity generated by focal stimulation of one retinal region induces opposite,

greenness activity in surrounding or functionally related neural tissue, and vice versa; and similarly for the yellow-blue and black-white neural processes. The strength of the induced response is related to the strength of the focally elicited activities in each of the mutually interacting areas, and it is also related to the spatial contiguity of the areas in question. Thus, the formulation subsumes a particular demonstration by Land that seems to have caused special puzzlement. This is the demonstration that the variety of hues elicited by a two-color photograph of a random array of colored papers is reduced to a very nearly monochromatic series when the same papers are photographed in an ordered sequence arranged side by side in terms of similarity.

The strength of the opponent interactions is maximal for contiguous areas, but in a graded series these mutual effects will differ very little since the stimulation differences in contiguous areas have been minimized by the similarity ordering. Thus, the graded series minimizes contrast effects which can be very strong for the same array of samples in a random spatial arrangement which provides significantly greater stimulation differences between the most strongly interacting contiguous areas.

In summary, we should like to repeat that we think the area of color vision has been plagued by an inordinate amount of conceptual confusion. Some of this confusion may be attributed to the coexistence of multiple and partially overlapping languages, specialized, technical, and non-technical, used to describe the phenomena and in their analysis. Much of it, we believe, may be attributed to the coexistence of two competing paradigms and all of their attendant misunderstandings and misconceptions. Optimistically, we see a convergence of scientific views in the not too distant future. We do not think this convergence will come about by echoing the currently fashionable assertion that "Helmholtz was right in the periphery and Hering was right in the center." What this leads to is assigning one color code (Helmholtz's) to the receptors and then changing it (to Hering's) for the neural activities stimulated by the receptor light absorptions. "Blue" receptor activities would have to stimulate "redness" when they feed into the red-green opponent system, the "red" cone would generate "yellowness" when it synapses with the yellow-blue neural process, and so on. It will not help much to eliminate competition between color theories if we then have to crack competing color codes.

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Review by Jo Ann S. Kinney. (By permission, Contemporary Psychology, 1969, 14(5), 287.)

In his introduction Joseph Sheppard presents an excellent discussion of his reasons for writing the book. The myriad of data available in the literature from many disciplines present the newcomer to the field with an almost impossible task, not only because of its enormity, but also due to the often conflicting nature of the results. "How is he (the newcomer) to distinguish among established experimental fact, generally accepted theory, and disputed hypotheses"? Sheppard's goal of compiling a syllabus or "ordered discussion" of many of the topics in color vision is a laudable one.

To some extent, Sheppard is successful in meeting this goal; certain sections do provide a comprehensive and meaningful summary of vast amounts of data. The first several chapters are good examples. The discussion of the Standard Observer is, as Sheppard warns, not the standard presentation, but it is a clear and essentially fair discussion of a topic that is often difficult for the newcomer. To a psychologist, for whom education in

color starts with hue, brightness, and saturation, the only peculiarity is the choice of starting a book on color vision with an extremely specialized topic familiar mainly to engineers, lighting specialists, and color technologists.

An excellent contribution is made in the chapter on retinal sensitivity, where the author has compiled, in single figures, 96 luminosity curves from different investigations according to whether threshold, brightness match, or flicker methods were employed. The psychologist, more familiar with individual differences, may reach conclusions at variance with the author. Nevertheless, the compilation provides the reader with an overview of the foveal luminosity function not to be found elsewhere.

In other sections, however, a knowledgeable reader will take exception not only to the conclusions reached, but, more importantly, to the selection of the references for inclusion. This becomes increasingly true as the author develops his own theory of color vision, a curious combination of wave-guide modes in human cones, bipolar tripartition, and the single cell recordings of De Valois in the lateral geniculate body.

The bipolar speculation is based on the classic work of Polyak rather than the new electron microscope studies of Dowling. The description of the recordings from the lateral geniculate body is from De Valois's 1960 work; the point particularly emphasized by Sheppard was rescinded in De Valois's 1965, 1966, and 1967 publications. The statements concerning the lack of evidence for cone photopigments are in flat contradiction to those of the vast majority of authors in the field.

Many more examples could be cited. It is perhaps sufficient to state that this reviewer took exception to the selection of references (either as being outdated or biased) in the following areas: the trianopic effect in normal color vision; the correspondence between color zones and physiology; the discussion of flicker fusion data as an example of distinct metabolic organizations in the rods and cones; the Land effect; the reported rise times for different colors; and the implication that photochemical bleaching has been used in pre-Sheppard times to explain temporal color effects.

Sheppard has written essentially a theory of color vision, not an ordered discussion of color vision. He has, I am afraid, fallen short of his goal, adding to, rather than easing, the newcomers' problems when entering the field.

Review by I. Nimeroff. (By permission, Physics Today, June 1969, 81.)

In recent years information theory, developed to process and understand experimental data, has been extended to speculation about how the brain processes the

stimulus information it receives. The subtitle of this short book by Joseph Sheppard indicates that the author critically reviews the experimental data of color perception but does not convey the idea that the critique will take on the information-theory approach.

This book, written by a comparative tyro in the field of color vision, is intended for scientists and engineers to whom knowledge about human visual processes is important for their research and work. The author is to be commended for having covered so many topics of the physics, physiology and psychology of color vision in a book of less than 200 pages. This brevity was accomplished by the author's generally clear and concise writing style that fails, however, to treat with sufficient depth the subject matters about which he complains. For instance, on pages 23, 39 and 47, he is critical of the use of average spectral tristimulus values and luminous-efficiency values to represent all observers or any one observer. Sheppard, however, has not reviewed the literature sufficiently deeply to have found the readily available work of David L. MacAdam, W. R. J. Brown, Gunter W. Wyszecki, and myself on the variability within and among observers.

Sheppard has criticized a wide variety of related topics, the collection of which is not to be found within the covers of any other book. Such a collection, if treated in depth, would have been extremely useful had it been written as late as 15 years ago. The terms, definitions and symbols Sheppard uses would have been consistent with those used then and could have had a strong influence on the direction of research. As it is, he leads the reader to wonder whether some of his criticisms in a field one step removed from the reader's main interest are no longer justified.

I found the chapters on the psychology and physiology of color perception reasonably informative. These chapters should serve physicists as a ready source of reference to these topics. In Chapter III, Sheppard also shows that he has a penetrating understanding of the concept of metamers. The treatment of the other physical aspects of color vision in this book is not quite adequate however. It may be that psychologists and physiologists will have the same opinion about the manner in which their respective specialties were presented.

Despite the shortcomings of this book, I recommend the acquisition of it by all who have an interest in color-vision investigation. No scientific field should be above a critical appraisal.

## MISCELLANY

### Word Colors

As proposed by Marsteller, Inc. in an ad in Time (July 18, 1969), words have colors and color words have age. For example: Passion, rape, explode, smash, murder,



and attack are Red. Brook, cool, comfort, meander, persuade, and hammock are Green. Glower, agitate, dictator, anarchy, and cloak are Black. Unctuous, abstruse, surrender, clerk, listen, observe, and gloat are Beige. Black is said to be old, but yellow -- "almost opposite on the spectrum" -- is young. Orange is as young as yellow, and brown is middle-aged. Purple is younger than lavender and slower than violet, which is extremely fast!

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#### Color Me Nostalgic

Old timers can remember  
If their memories are fairish,  
When what now is psychedelic  
Was frowned upon as garish,  
And -- proclaim it from a steeple --  
When colors clashed, not people.

-- Richard Armour.

(From the Wall Street Journal, by permission)

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