EXPERIMENTS IN COLOR VISION

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From childhood onward we enjoy the richness of color in the world around us, fascinated by the questions: "How do we see color? How do you know you see the same color I do? Why do colors sometimes mix to give quite different colors?" Since 1660, when Isaac Newton discovered the properties of the visible spectrum, we have slowly been learning the answers; and we are finding that the beauty of the outer world is fully matched by the technical beauty of the mechanisms whereby the eye sees color.

No student of color vision can fail to be awed by the sensitive discernment with which the eye responds to the variety of stimuli it receives. Recently my colleagues and I have learned that this mechanism is far more wonderful than had been thought. The eye makes distinctions of amazing subtlety. It does not need nearly so much information as actually flows to it from the everyday world. It can build colored worlds of its own out of informative materials that have always been supposed to be inherently drab and colorless.

Perhaps the best way to begin the story is to consider two sets of experiments. The first is the great original work of Newton, which set the stage for virtually all research in color vision since that time. The second is an apparently trivial modification that reverses some of his basic conclusions.

As is so often the case with truly revolutionary insights, the simplicity of Newton's discovery causes one to wonder why no one before him had made it. He passed a narrow beam of sunlight through a prism and found that it fanned out into the band of colors we know as the visible spectrum: red, orange, yellow, green, blue, indigo and violet. When he reversed the process, gathering the beam together with a second prism, the colors vanished and white light reappeared. Next he tried recombining only parts of the spectrum, inserting a slotted board to cut off all but certain selected bands [*see diagram on page 290*]. When he combined two such bands of color, letting the rays mix on a screen, a third color appeared, generally one matching a color lying between the bands in the spectrum.

Let us repeat this last experiment, placing the openings in the board just inside the ends of the narrow yellow band in the spectrum. When these two yellow beams strike the screen, they combine, as Newton observed, to produce yellow.

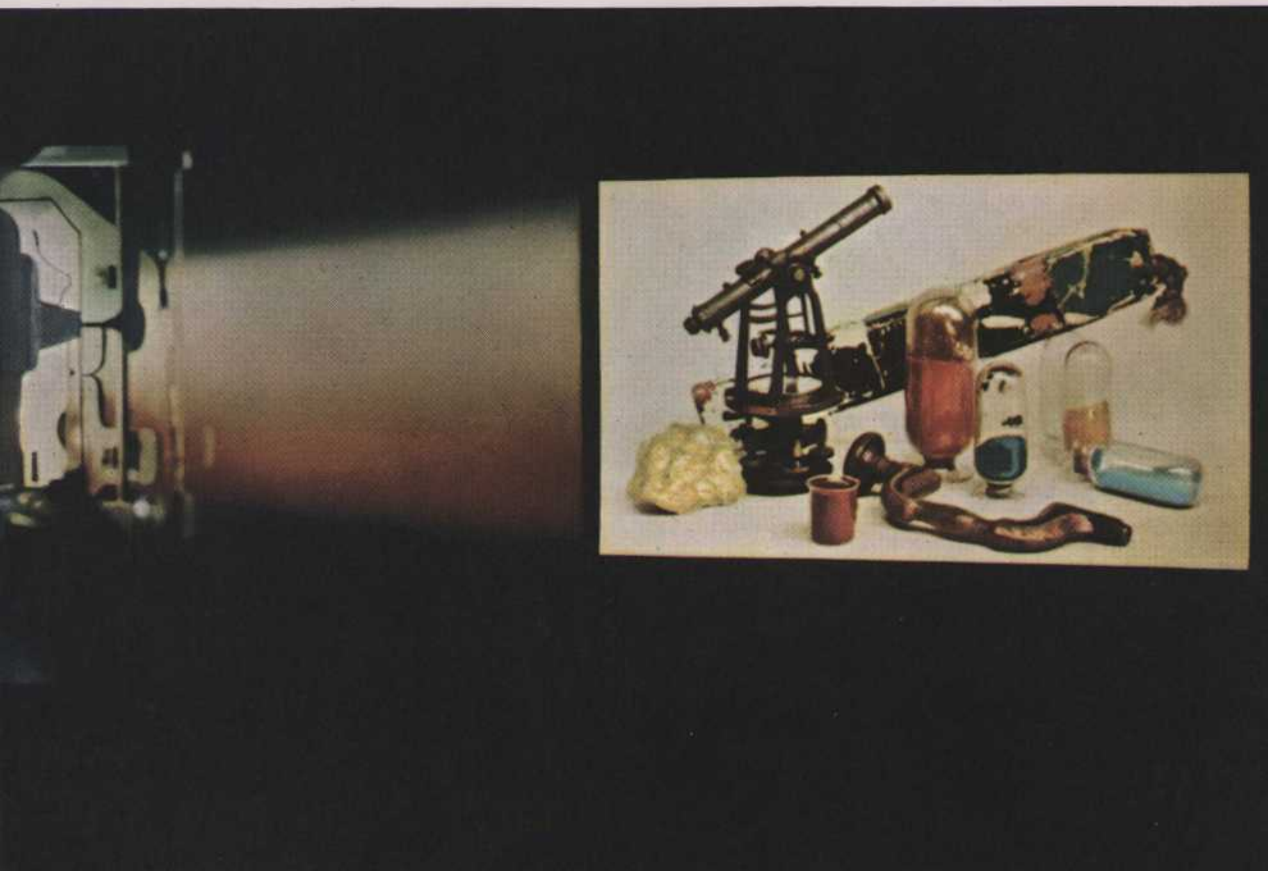
Now for our modification. In front of the slits we place a pair of black-and-white photographic transparencies. Each shows the same scene: a collection of variously colored objects. There is, of course, no color in the photographs. There are simply lighter and darker areas, formed by black silver grains on transparent celluloid. A glance at the two shows that they are not absolutely identical. Some of the objects in the scene are represented by areas which are lighter in the first photograph than in the second. Others are darker in the first and lighter in the second. But all that either photograph can do is to pass more or less of the light falling on its different regions.

The yellow beams pass through these transparencies and fall on the screen. But now they are not yellow! Somehow, when they are combined in an image, they are no longer restricted to producing their spectral color. On the screen we see a group of objects whose colors, though pale and unsaturated, are distinctly red, gray, yellow, orange, green, blue, black, brown and white [*see bottom photograph on page 288*]. In this experiment we are forced to the astonishing conclusion that the rays are not in themselves color-making. Rather they are bearers of information that the eye uses to assign appropriate colors to various objects in an image.

The Old Theory

This conclusion is diametrically opposed to the main line of development of color theory, which flows from Newton's experiments. He and his successors, notably Thomas Young, James Clerk Maxwell and Hermann von Helmholtz, were fascinated by the problem of simple colors and the sensations that could be produced by compounding them. Newton himself developed quite good rules for predicting the colors that would be seen when various spectral rays were mixed to form a spot of light on a screen. These rules can be summarized in geometrical diagrams, one of the oldest of which is the color triangle [*see diagram at top of page 14*]. On modern versions of it we can read off the result of com-

COLORED OBJECTS in the top picture on the opposite page were photographed with the special dual camera which appears at left. Here the two ground-glass screens of the camera are left uncovered to show that one image is photographed through a green filter and the other through a red filter. The images are photographed on ordinary black-and-white film; then black-and-white positive transparencies are made from the negatives. In the bottom photograph the "red" transparency is projected through a red filter and the "green" without a filter. When the two images are superimposed on the screen at right, they reproduce the objects in a full range of color.

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bining so many parts of color A with so many of color B.

Once it was discovered that light is a wave motion, the classical investigations of color acquired a deeply satisfying logical basis. The order of colors in the spectrum follows wavelength, the longest visible wavelength falling at the red end of the spectrum and the shortest at the violet end. A pure color would be a single wavelength; compound colors would be mixtures of pure colors.

In trying to match colors by mixing spectral stimuli Maxwell and Helmholtz found that three different wavelengths were enough to effect all matches, and that those wavelengths had to be chosen from the red, green and blue bands of the spectrum. Accordingly red, green and blue came to be called the primary colors. On the basis of this evidence they proposed a three-color theory of color vision. We need not go into the details here. The central idea is that the eye responds to three different kinds of vibration, and that all color sensation is the result of stimulating the three responses in varying degrees of strength. Thus 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.

Now, as we have seen in our modification of Newton's experiment, the light at any point on the screen was composed of only two "yellow" wavelengths, yet the image was fully colored. And, as we shall see later, the colors in images will be remarkably stable even when the over-all relative strengths or intensities of the two wavelengths are varied.

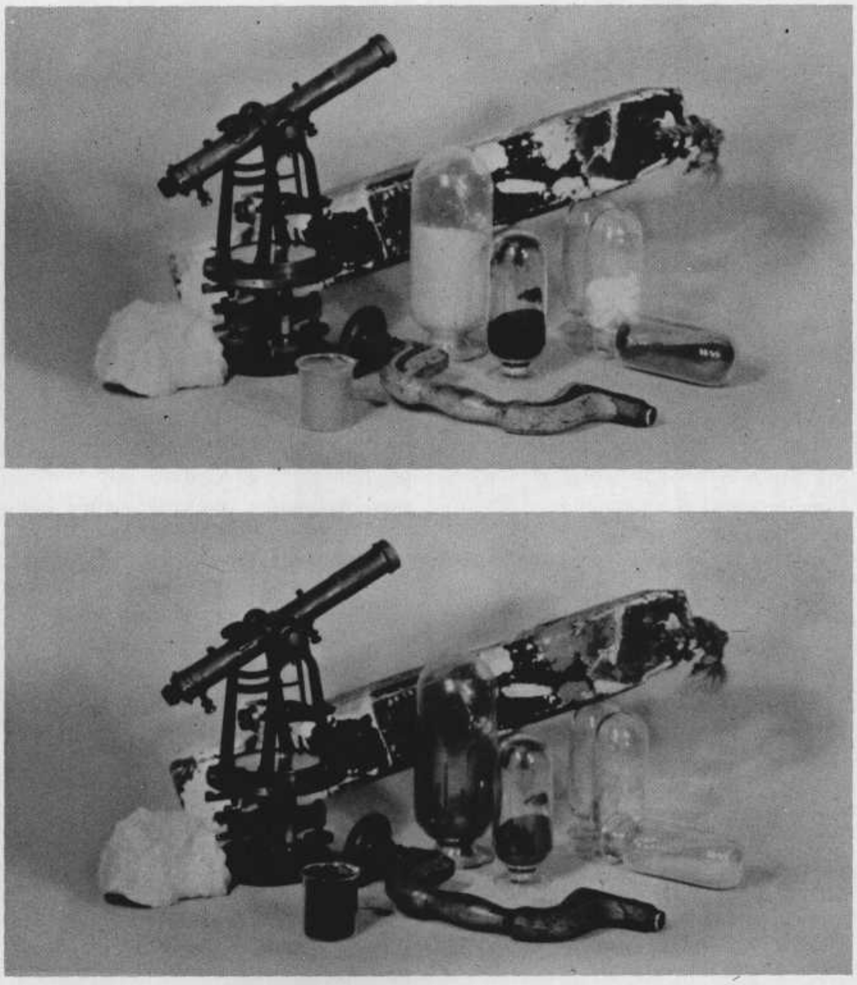
Natural Images

Is something "wrong" with classical theory? This long line of great investigators cannot have been mistaken. The answer is that their work had very little to do with color as we normally see it. They dealt with spots of light, and particularly with pairs of spots, trying to match one to another. The conclusions they reached were then tacitly assumed to apply to all of color sensation. This assumption runs very deep, and has permeated all our teaching, except for that of a few investigators like E. Hering, C. Hess and the contemporary workers Dorothea Jameson and Leo M. Hurvich (who have studied the effect produced on a colored spot by a colored surround).

The study of color vision under natural conditions in complete images (as opposed to spots in surrounds) is thus an unexplored territory. We have been working in this territory—the natural-image situation, as we call it—for the past five years. In the rest of this article I shall describe some of the surprises we have encountered.

To form the image in our modification of Newton's experiment we needed two sets of elements: a pair of different photographs of the same scene, and a pair of different wavelengths for illuminating them. It is possible to make the pictures different by tinkering in the laboratory, arbitrarily varying the darkness of their different areas. But, as every photographer will have recognized at this point, a simple way to produce the two pictures is to make "color separations", that is, to photograph the scene through two filters that pass different bands of wavelengths. In this way the film is systematically exposed to longer wavelengths coming from the scene in one case, and to shorter wavelengths in the other. In our investigations we usually use a red filter for the longer wavelengths and a green filter for the shorter.

Now when we illuminate the transparencies with practically any pair of wavelengths and superimpose the images, we obtain a colored image. If we send the longer of the two through the long-wave photograph and the shorter through the short-wave photograph, we



LONG AND SHORT RECORDS are provided by transparencies of these black-and-white photographs made through a red filter (*top*) and a green filter (*bottom*). In projection the long record (*top*) is illuminated by the longer of two wavelengths or bands of wavelengths, and the short record is illuminated by the shorter wavelength or band of wavelengths.

COLORS SEEN when long and short records are illuminated by closely spaced narrow bands of wavelengths are reproduced in these "Flexichrome" photographs. The illuminating wavelengths are indicated by arrows on the spectrum under each photograph. These images could not be photographed directly; the response of color film to the limited range of wavelengths used here is very different from that of the eye. SCIENTIFIC AMERICAN has artificially reproduced the colors seen by the eye by adjusting the color in a Flexichrome print.

obtain most or all of the colors in the original scene and in their proper places. If we reverse the process, the colors reverse, reds showing up as blue-greens and so on.

Long Wavelengths *v.* Short

It appears, therefore, that colors in images arise not from the choice of wavelength but from the interplay of longer and shorter wavelengths over the entire scene. Let us now test this preliminary hypothesis by some further experiments.

There are several more convenient ways to combine images than in the arrangement of Newton's experiment. One of the simplest is to place the transparencies in two ordinary projectors, using filters to determine the illuminating wavelengths. The color photograph at the bottom of page 287 shows images formed in this way.

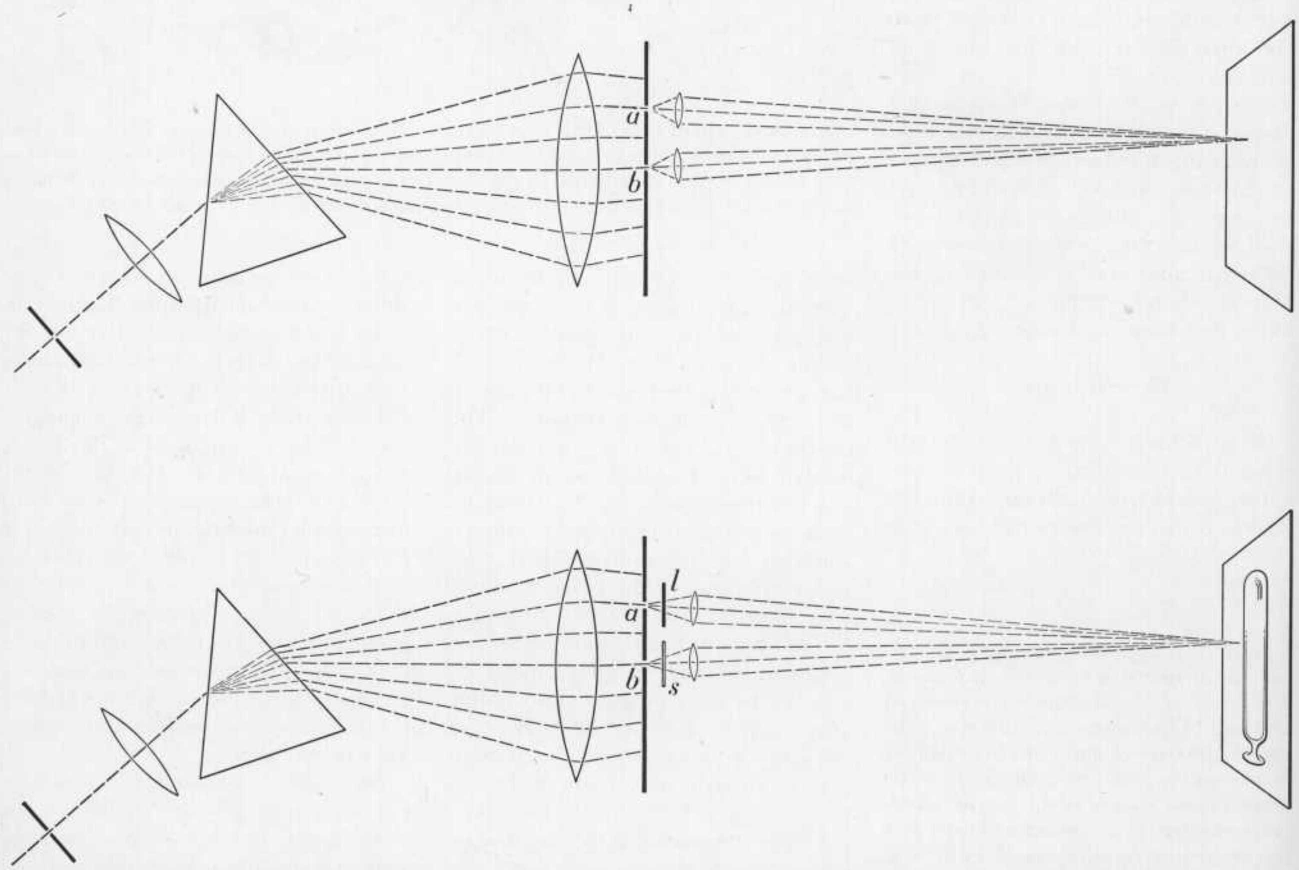
When we work with filters, we are not using single wavelengths, but rather bands of wavelengths; the bands have more or less width depending on the characteristics of each filter. It turns out that the width of the band makes little difference. The only requirement is that the long-wavelength photograph, or, as we call it, the "long record," should be illuminated by the longer band and the "short record" by the shorter band. Indeed, one of the bands may be as wide as the entire visible spectrum. In other words, it may be white light. The lower photograph on page 287 shows the result of using a red filter for the long record and no filter (that is, white light) for the short record.

One advantage of this arrangement is that an observer can test the truth of our hypothesis in a simple and dramatic way. According to classical theory the combination of red and white can result in nothing but pink. With no photograph in either projector, and with a red filter held in front of one of them, the screen is indeed pink. Now the transparencies are dropped into place and the view changes instantly to one of full, vivid color. If the red filter is taken away, the color disappears and we see a black-and-white picture. When the filter is put back, the colors spring forth again.

An incidental advantage in using red for the long record and white for the short lies in the fact that the colors produced look about the same to color film as they do to the eye. Thus the image can be photographed directly. With more restricted bands of wavelengths the film, which does not have the newfound versatility of the eye, cannot respond as the eye does, and reproductions must be prepared artificially [*see photographs on page 288*].

The projectors afford a simple way of testing another variable: brightness. By placing polarizing filters in front of the projector's lenses we can vary the amount of light reaching the screen from each source. With no transparencies in the projector, but with the red filter still over one lens, the screen displays a full range of pinks, from red to white, as the strengths of the two beams are changed. When the photographs are in place, the colors of the image on the screen hold fast over a very considerable range of relative intensities.

Let us pause for a moment to consider the implications of this last demonstration. Remember that the photographs

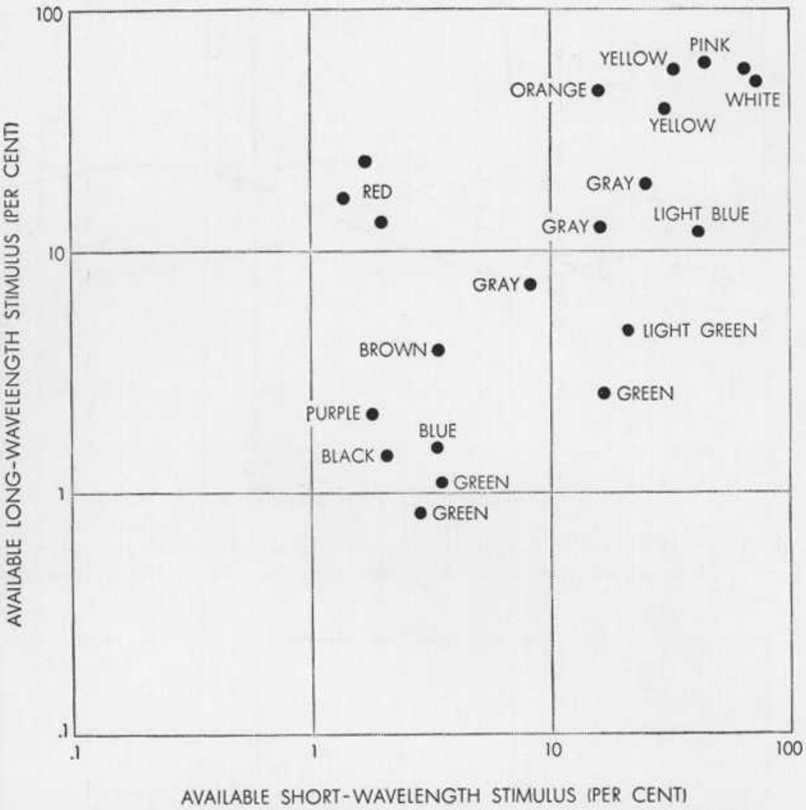


NEWTON'S EXPERIMENT in mixing spectral colors is shown schematically at top; the author's modification of the experiment, in which a pair of black-and-white transparencies is inserted in the beams, is diagrammed at bottom. When slits *a* and *b* are both in the yellow band of the spectrum, Newton's arrangement produces a spot of yellow on the screen. The image at bottom contains a gamut of color. The letters *l* and *s* in this diagram and others in this article refer, respectively, to the long record and the short record.

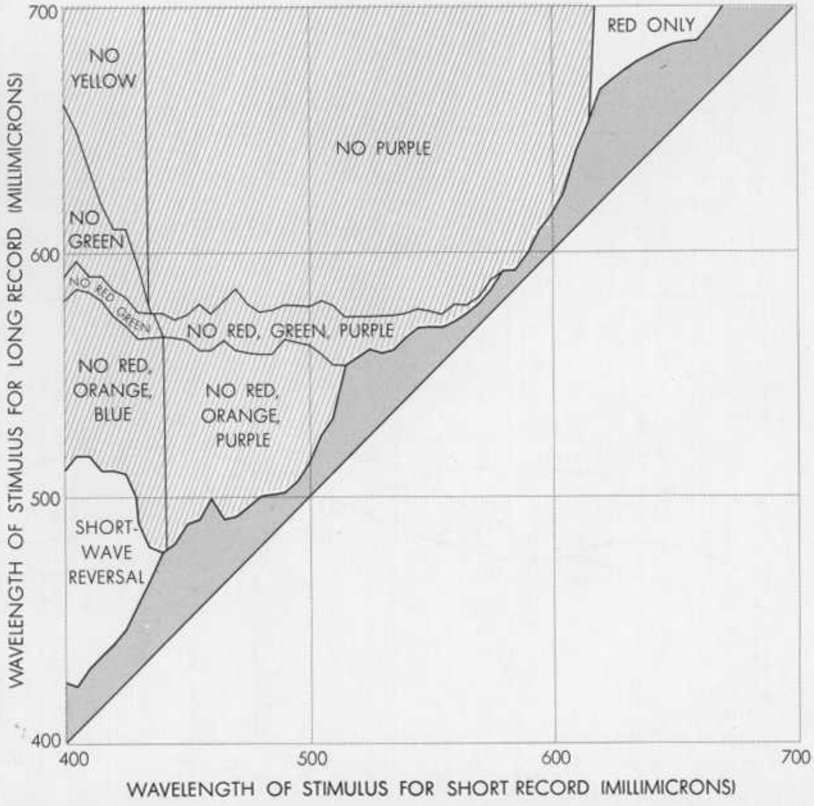
are nothing but pieces of celluloid treated to pass more light in some places than in others. All they can do to the red and white beams is to change relative intensities from point to point. In doing so they stimulate a complete gamut of color. Yet when we vary the relative intensities of the beams over the whole field of view, the colors stay constant. Evidently, even though the eye needs different brightness ratios, distributed over various parts of the image, to perceive color, the ratios that the eye is interested in are not simple arithmetic ones. Somehow they involve the entire field of view. Just how they involve it we shall see a little later.

The dual-projector system is convenient, but it is not a precision instrument. The wavelengths it can provide are limited by the characteristics of available filters. Narrow band-width filters may be used, but they seriously restrict the quantity of light. My colleague David Grey has therefore designed for me a dual image-illuminating monochromator [*see illustration on page 296*]. This instrument contains a pair of spectroscopes which allow us to light our transparencies with bands as narrow as we choose and of precisely known wavelength. By blocking off the spectroscopes and using filters, we can also obtain white light or broad bands. The two images are combined by means of a small, semitransparent mirror; light from one record passes through the mirror, and light from the other is reflected from its top surface. The intensity of each light source can be closely controlled.

With the dual monochromator we have confirmed our broad hypothesis: Color in natural images depends on a varying balance between longer and shorter wavelengths over the visual field. We have also been able to mark out the limits within which color vision operates. It turns out that there must be a certain minimum separation between the long-record wavelength and the short. This minimum is different for different parts of the spectrum. Any pair of wavelengths that are far enough apart (and the minimum distance is astonishingly small) will produce grays and white, as well as a gamut of colors extending well beyond that expected classically from the stimulating wavelengths. Many combinations of wavelengths produce the full gamut of spectral colors, plus the nonspectral color sensations such as brown and purple. All this information has been summarized in a color map showing the limitations on the sensations produced by different pairs of wave-



COORDINATE SYSTEM predicts colors in natural images. Axes are dimensionless, each measuring illumination at every point as a percentage of the maximum that could be there.



COLOR MAP shows limits on color obtainable with different pairs of wavelengths. The gray area is an achromatic region in which wavelengths are too close together to produce any kind of color. In the region marked "short-wave reversal" the colors are normal, but the short wavelengths act as the stimulus for the long record and the long wavelengths as the stimulus for the short record. The blank area below the diagonal is a region of reversed color obtained by illuminating the short record with long wavelengths and *vice versa.*

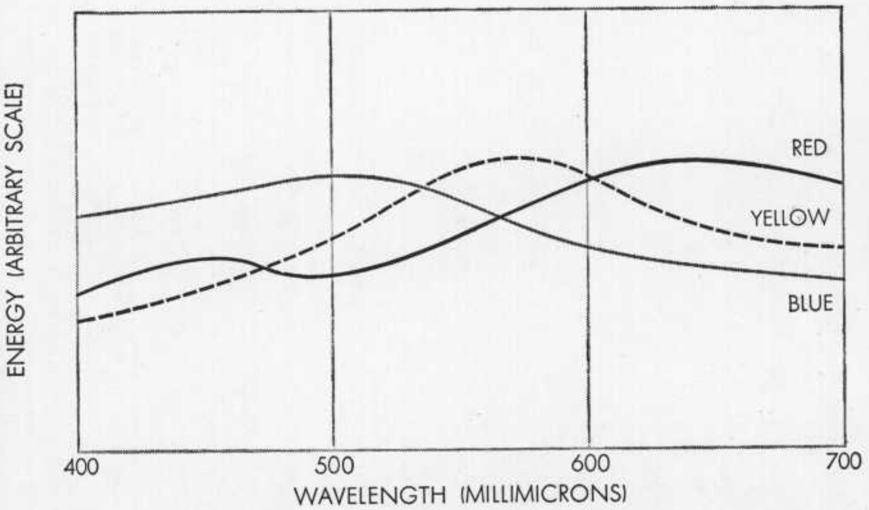
lengths [*see illustration at bottom of preceding page*]. We have also investigated the limits on relative brightness. With some pairs the colors are maintained over enormous ranges of brightness; with others they begin to break down with smaller changes. Again, the result depends on the wavelengths we are using. A table showing the stability of various colors for a sample pair of wavelengths appears on page 297.

A New Coordinate System

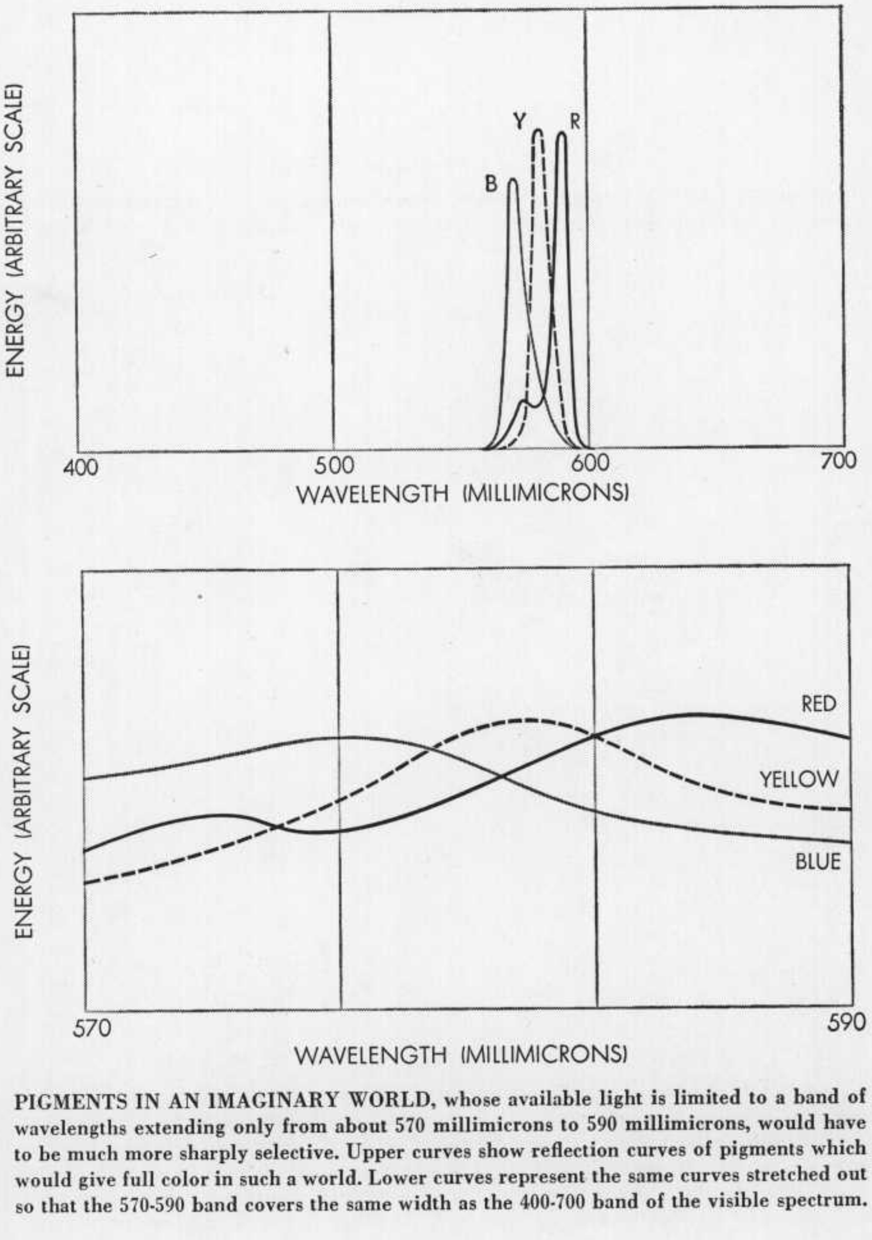
The color map tells us what we will *not* see when we combine a pair of images at various wavelengths. Can we now make a positive prediction? Given a pair of records of the same scene, and a pair of wave bands with which to illuminate them, what color will appear at each specific point on the combined image? In other words, we want a set of rules that will do for images what the color triangle does for color-matching experiments (and what most of us have mistakenly supposed it does for images as well).

We have formed a new coordinate system that does for the first time predict the colors that will be seen in natural images. Perhaps the best way to approach it is through an actual experiment. Let us set up the dual projector (or the monochromator) for any pair of "long" and "short" bands, say red and white, that can produce full color. We know that local variations in the relative brightness of the two records must somehow give rise to the color. Yet we have also found that changing all the brightness ratios in a systematic way, for example by cutting down the total light from the red projector, has no effect. Therefore we look for a way of describing the brightness in terms that are independent of the total light available in either image.

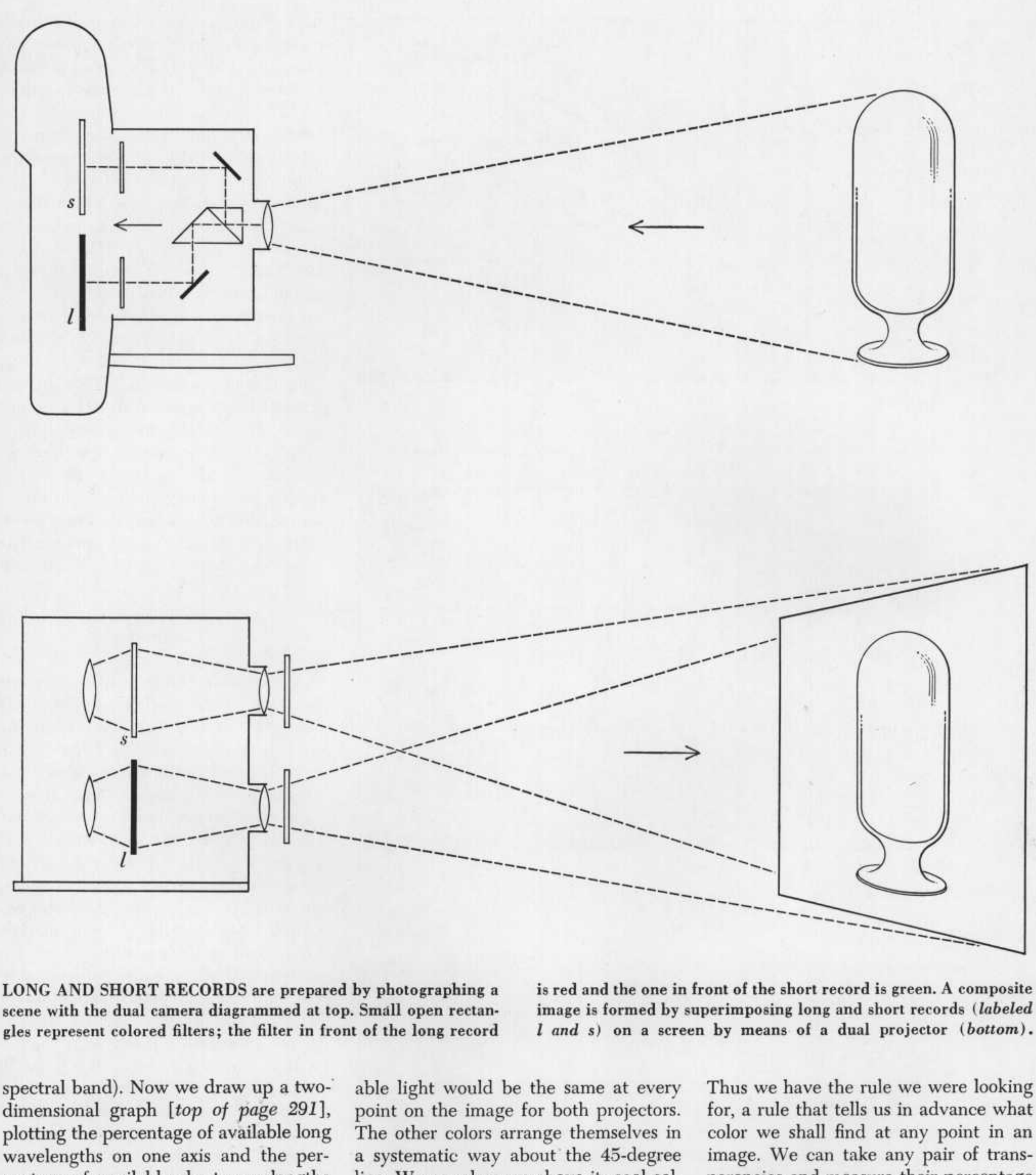
This can be done as follows: We turn on the "long" projector alone, setting its brightness at any level. Now we find the spot on the red image corresponding to the point at which the long black-and-white record lets through the most light. We measure the intensity at that point and call it 100 per cent. It tells us the maximum available energy for the long waves. Next we measure the intensity of the light all over the rest of the red image, marking down for each point the red intensity as a per cent of the maximum available. Then we turn off the "long" projector, turn on the "short" one and follow the same procedure for the short wavelengths (in this case the full



PIGMENTS IN OUR WORLD have broad reflection characteristics. Each pigment reflects some energy from wavelengths across the visible spectrum (400 to 700 millimicrons).



PIGMENTS IN AN IMAGINARY WORLD, whose available light is limited to a band of wavelengths extending only from about 570 millimicrons to 590 millimicrons, would have to be much more sharply selective. Upper curves show reflection curves of pigments which would give full color in such a world. Lower curves represent the same curves stretched out so that the 570-590 band covers the same width as the 400-700 band of the visible spectrum.



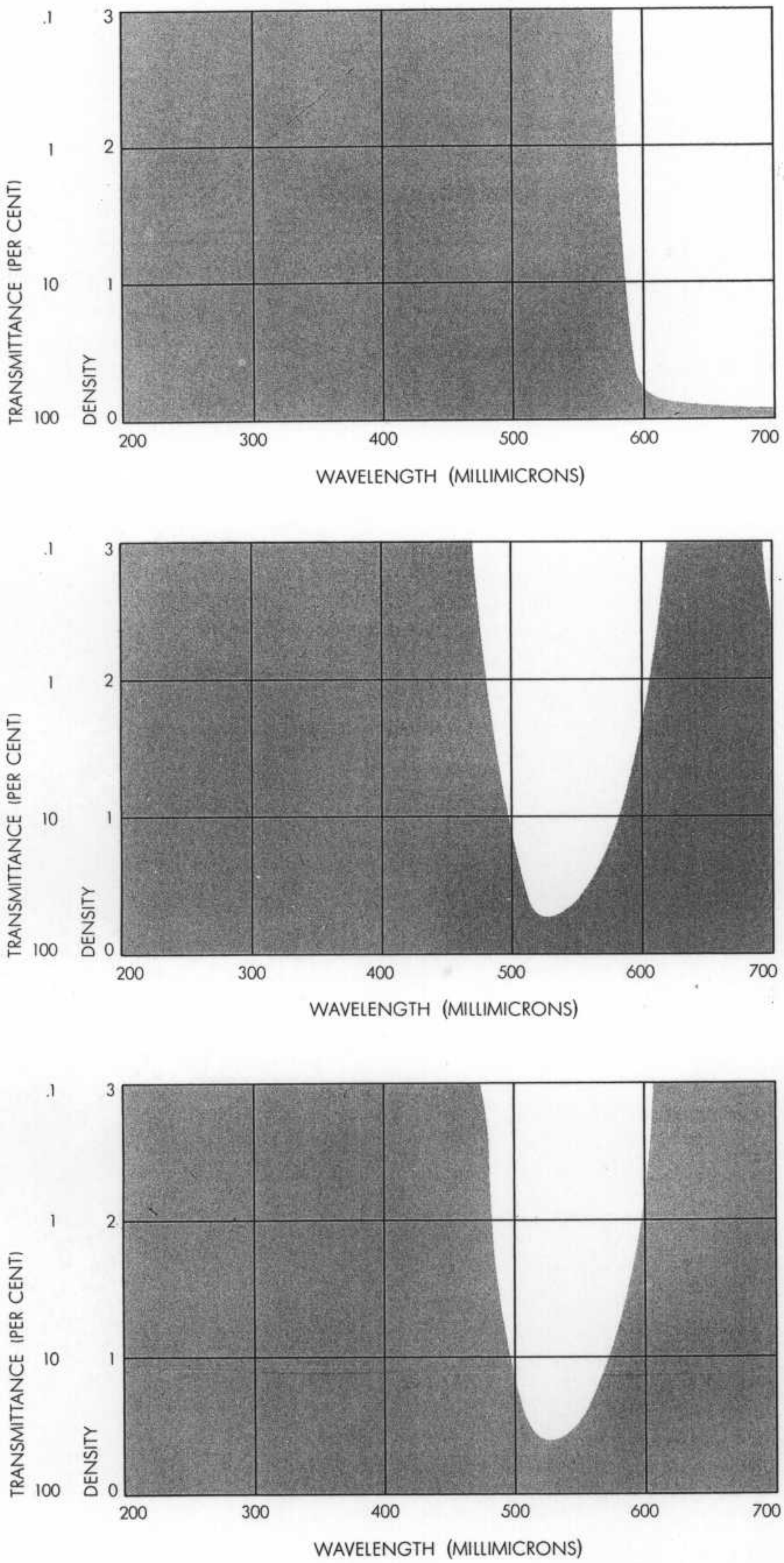
LONG AND SHORT RECORDS are prepared by photographing a scene with the dual camera diagrammed at top. Small open rectangles represent colored filters; the filter in front of the long record is red and the one in front of the short record is green. A composite image is formed by superimposing long and short records (*labeled l and s*) on a screen by means of a dual projector (*bottom*).

spectral band). Now we draw up a two-dimensional graph [*top of page 291*], plotting the percentage of available long wavelengths on one axis and the percentage of available short wavelengths on the other. Every point on the image can be located somewhere on this graph. Each time we plot a point, we note next to it the color it had on the image.

What emerges is a map of points, each associated with a color. When it is finished, we can see that the map is divided into two sections by the 45-degree line running from lower left to upper right. This is the line of gray points. If we had put the same transparency in each projector, all the points would fall on the gray line, since the percentage of available light would be the same at every point on the image for both projectors. The other colors arrange themselves in a systematic way about the 45-degree line. Warm colors are above it; cool colors are below. Thus it seems that the important visual scale is not the Newtonian spectrum. For all its beauty the spectrum is simply the accidental consequence of arranging stimuli in order of wavelength. The significant scale for images runs from warm colors through neutral colors to cool colors.

Repeating our experiment with different illuminating wavelengths or bands, we find that for every pair that produces full color the position of the colors on the coordinate graph remains the same. Thus we have the rule we were looking for, a rule that tells us in advance what color we shall find at any point in an image. We can take any pair of transparencies and measure their percentage of transmission in various regions of the picture. Then, before projecting them, we can predict the colors these areas will have. We will be right provided that the illuminating wavelengths are capable of stimulating all the colors. In cases where they are not, we must change the coordinate map accordingly. Thus the full set of rules consists of a group of coordinate color plots, one for each section of the color map at the bottom of page 291.

Note that each coordinate system is



WAVELENGTHS PASSED BY FILTERS used in various experiments described by the author are shown in these curves. At top is the transmittance curve for the red filter used in photographing long record; below it is transmittance curve of green filter for preparing short record. At bottom is curve for the green filter used in the sodium-viewer experiment.

itself dimensionless. The axes do not measure wavelength, brightness or any other physical unit. They express a ratio of intensities at a single wavelength or for a broad band of wavelengths. The axes have another interesting property: they are stretchable. Suppose we superimpose two identical long-wavelength photographs in the slide holder of the "long" projector and leave a single short-wavelength photograph in the holder of the "short" projector. We find that this combination still does not alter the colors on the screen. What sort of change have we made? Every point in the long record that transmitted 1/2 of the available light now transmits 1/4, points that transmitted 1/5 now transmit 1/25 and so on. On the logarithmic scale of our graph this corresponds to stretching the long-record axis to twice its former length. The 45-degree line now shifts to a new direction, but all the color points shift with it, maintaining their relative positions [*see diagram on opposite page*].

Randomness

Our studies of the coordinate graph have uncovered another interesting and subtle relationship. As we plotted graphs for various experiments we began to suspect that any arrangement which yielded points falling on a straight line, or even on a simple smooth curve, would be colorless. To test this idea we tried putting a negative photograph in one projector and a positive of that negative in the other. Such a pair of images will plot as a straight line running at right angles to the 45-degree gray line. The image is indeed virtually colorless, showing only the two "colors" of the stimuli involved in projection and a trace of their Newtonian mixture.

If an image is to be fully colored, its coordinate graph must contain points distributed two-dimensionally over a considerable area. But even this is not enough. The points must fall on the graph in a somewhat random manner, as they do in the plot of any natural scene. This requirement can be demonstrated in a very striking experiment. Suppose we put a "wedge" filter in the slide holder of the red projector. The effect of the filter is to change the intensity of the beam continuously from left to right. That is, when the red projector is on and the white projector off, the left side of the screen is red and the right side is dark, with gradations in between. Now we place a similar wedge, but vertically, in the white projector so that the top of the screen is white and the bottom is dark. With both projectors turned on we now have an infinite variety of red-to-white ratios on the screen, duplicating all those that could possibly occur in a colored image. However, they are arranged in a strictly ordered progression. There is no randomness. And on the screen there is no color —only a graded pink wash.

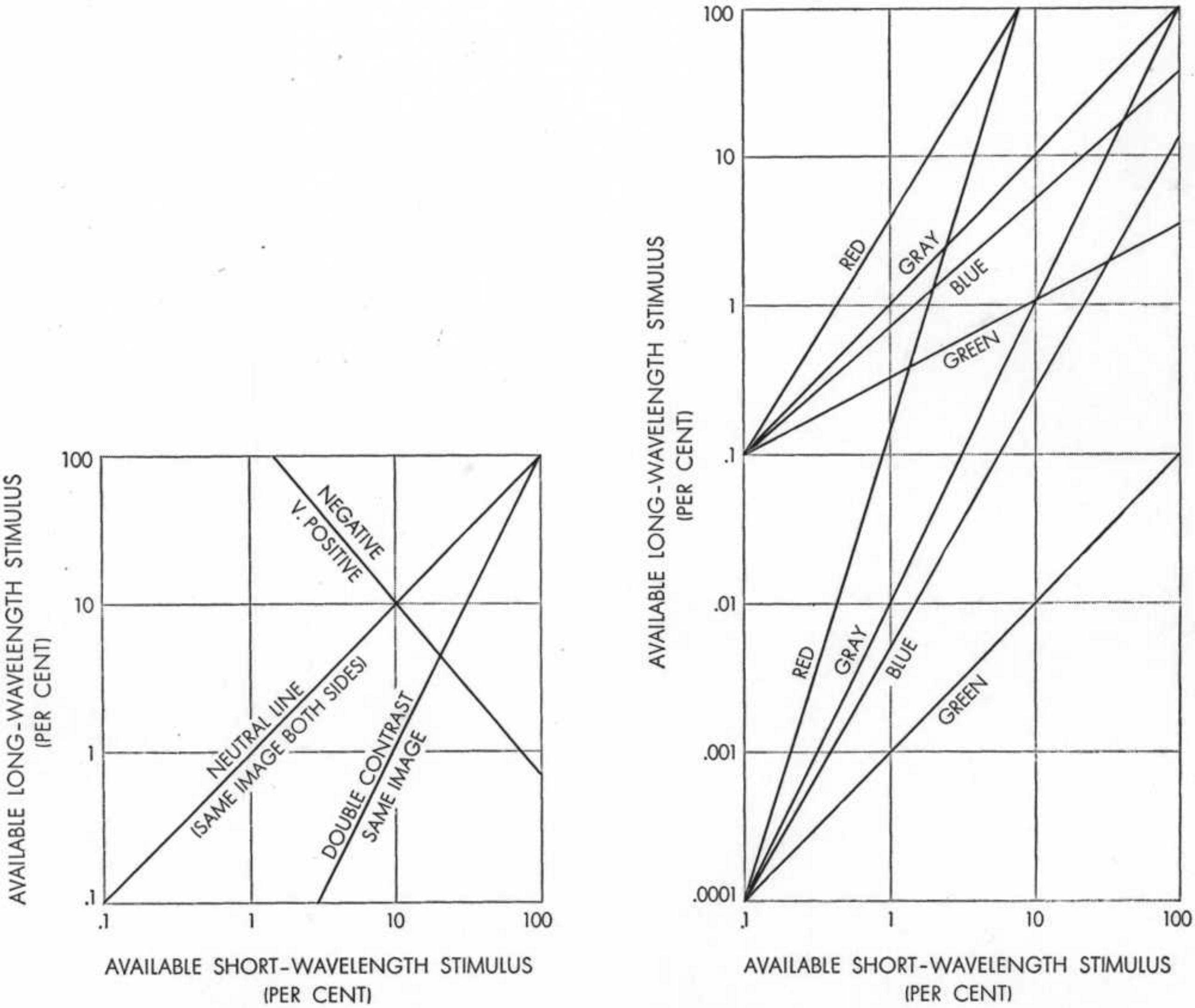
To repeat, then, the colors in a natural image are determined by the relative balance of long and short wavelengths over the entire scene, assuming that the relationship changes in a somewhat random way from point to point. Within broad limits, the actual values of the wavelengths make no difference, nor does the over-all available brightness of each.

The independence of wavelength and color suggests that the eye is an amazingly versatile instrument. Not only is it adapted to see color in the world of light in which it has actually evolved, but also it can respond with a full range of sensation in much more limited worlds. A dramatic proof of this is provided by another series of experiments.

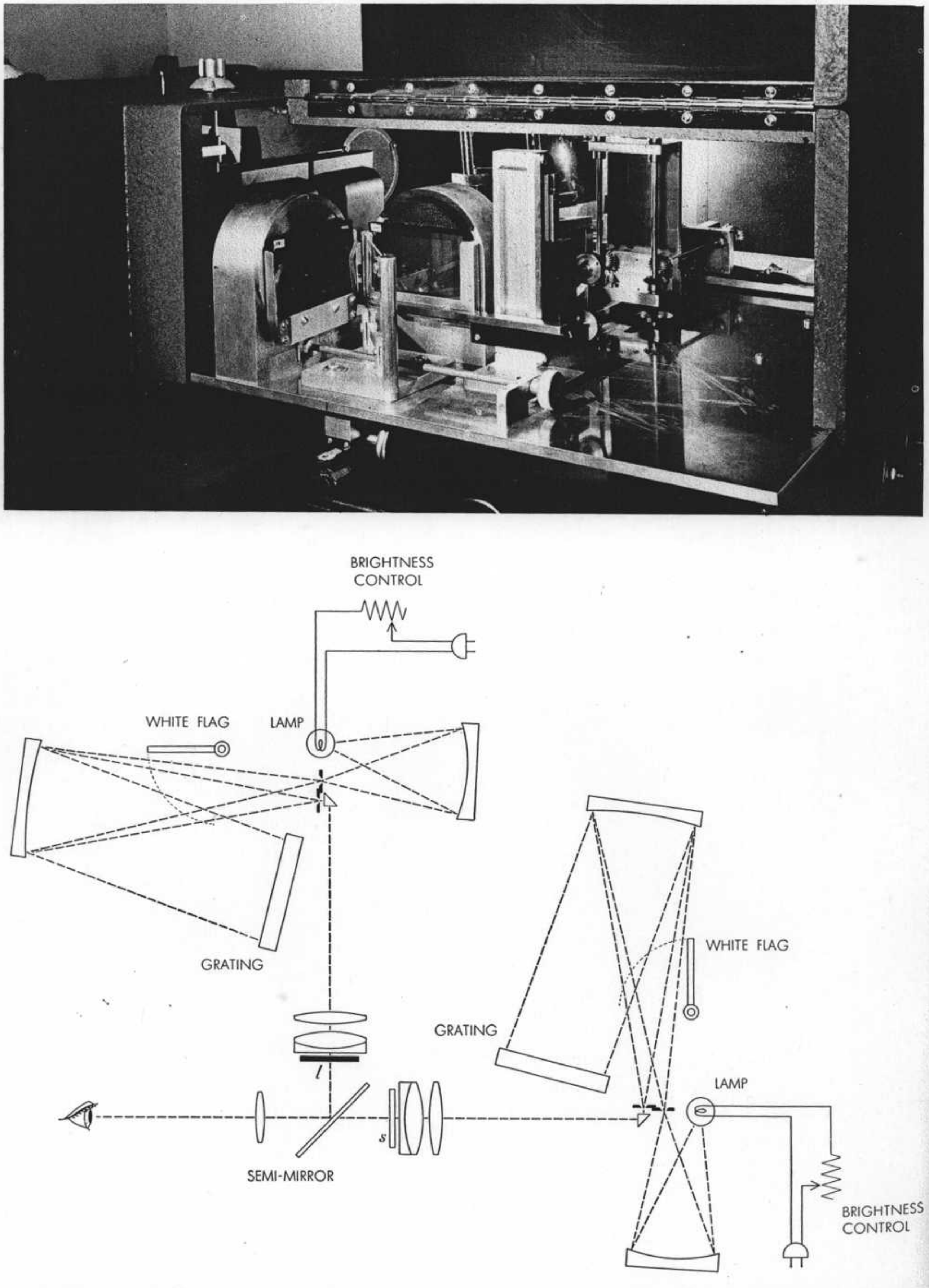
Color Worlds

In these we use a pair of viewing boxes that superimpose fairly large images by means of semitransparent mirrors [*see diagram at bottom of page* 297]. Each box contains tungsten lamps, which produce white light, to illuminate one record and a sodium lamp to illuminate the other. We turn on one viewer, inserting the long and short transparencies and placing a red filter over the tungsten lamp. The composite image is fully colored, containing greens and blues, although the shortest wavelength coming from the mirror lies in the yellow part of the spectrum. Now we turn on the second viewer, inserting a green filter over the white light-source. Again the image contains a gamut of color, including red. The observer can see the images in both viewers at once—each showing the same range of color, but representing different visual worlds. In the first the sodium light (with a wavelength of 589 millimicrons) serves as the shortest available wavelength and helps to stimulate the green and blue. In the second it is the longest wavelength and stimulates red. If the observer stands back far enough from the viewer, he can also see the "natural" colors in the room around him. Here then is a third world in which yellow is "really" yellow.

Another way to use the green filter in the second sodium viewer is to hold it



PROPERTIES OF COORDINATE SYSTEM are illustrated in these diagrams. At left are the graphs of experimental situations which do not produce a gamut of color in the image. Such situations appear to graph as straight lines. At right the axes are shown to be stretchable. When gray line dividing warm and cool colors is displaced, colors move but maintain their relative positions.



DUAL MONOCHROMATOR is seen in schematic diagram at bottom and in photograph at top. Very narrow bands of wavelengths from any part of the visible spectrum are produced by the two gratings. White flags can be inserted to give white light. Narrow rectangles marked *l* and *s* represent the black-and-white transparencies that serve as the long record and the short record respectively.

COLORS SEEN	RANGE OVER WHICH SEEN	VARIATION IN COLOR OVER THIS RANGE
GRAY	200 TO 1	LITTLE VARIATION
BROWN	100 TO 1	YELLOW-BROWN TO DARK BROWN
WHITE	100 TO 1	YELLOWISH-WHITE TO BLUISH-WHITE
YELLOW	30 TO 1	YELLOW TO OFF-WHITE
YELLOW-GREEN	30 TO 1	YELLOW-GREEN TO YELLOW ORANGE
BLUE	10 TO 1	BLUE-VIOLET TO BLUE GREEN
GREEN	6 TO 1	BLUE-GREEN TO GRAY-GREEN
RED	5 TO 1	DARK RED TO DARK ORANGE-RED
ORANGE	5 TO 1	YELLOW TO RED-ORANGE

LIMITS OF STABILITY of colors under variation in relative brightness of a sample pair of long and short stimuli are summarized in this typical chart. Second column shows the mechanism ratio (changing the brightness of either or both of the stimuli) for which color at left is recognizable. Pair of stimuli used was 450 millimicrons and 575 millimicrons.

up to the eye instead of placing it in front of the tungsten lamps. This filter passes both the sodium wavelength and the green band [*see bottom graph on page 294*]. When he looks around the room, the observer sees red objects as black and the rest of the colors as washed-out green. But when he looks at the picture in the second viewing box, he sees it quite full of color, including red.

The color worlds of the viewers are produced by pictures. Could we make physical models of these worlds, populating them with real objects which would show the same colors as the images in the viewers under the same conditions of illumination? We could if only we had the proper pigments. The pigments in the world around us are the best we have been able to find that look colored in our lighting: a spectrum of visible wavelengths from 400 to 700 millimicrons. Each of these pigments reflects a broad band of wavelengths, and its peak is not sharp [*see diagram at top of page 292*].

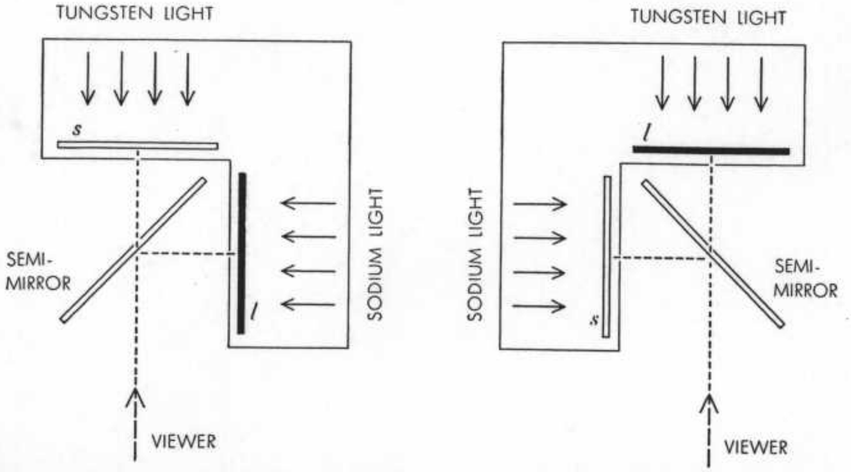
Thus our coloring materials do not distinguish clearly between wavelengths that are fairly close together. If we could find pigments with much narrower response curves, we would suspect that these might provide full color in a more restricted world of light—a world, for example, lighted by the wavelengths that pass through the green filter. In the absence of such coloring materials, we might content ourselves with creating this world photographically, if we could show that this is possible. A moment's study of the diagrams on page 292 will show the exciting fact that a two-color separation photograph in a world of any band-width is the same as a two-color photograph in a world of any other band-width—including our own, provided that we postulate that a correctly proportioned change in the absorption bands of the pigments goes along with a change in the band-width of the world. Therefore we can use our regular long and short pictures, taken through the red and green filters, to transport ourselves into new worlds with their new and appropriately narrow pigments.

The Visual Mechanism

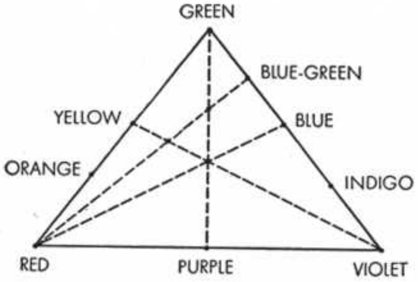
The sodium-viewer demonstration suggests an important consideration that we have not previously mentioned, although it is implicit in what has already been said. If the eye perceives color by comparing longer and shorter wavelengths, it must establish a balance point or fulcrum somewhere in between, so that all wavelengths on one side of it are taken as long and all on the other side as short. From the evidence of the viewer we can see that the fulcrum must shift, making sodium light long in one case and short in the other.

Where is the fulcrum in the ordinary, sunlit world? Experiments on a large number of subjects indicate that it is at a wavelength of 588 millimicrons. When we use this wavelength in one part of the dual monochromator and white light in the other, the image is nearly colorless. With a wavelength shorter than 588 millimicrons, white serves as the longer stimulus in producing color; with a wavelength longer than 588 millimicrons, white becomes the short record.

From the dual-image experiments we learn that what the eye needs to see color is information about the long and short wavelengths in the scene it is viewing. It makes little difference on what particular bands the messages come in. The situation is somewhat similar to that in broadcasting: The same information can be conveyed by any of a number of different stations, using different carrier frequencies. But a radio must be tuned to the right frequency. Our eyes are always ready to receive at any frequency



SODIUM-VIEWING BOXES are diagrammed schematically. Each of these instruments produces a large composite image by means of the semitransparent mirror. Tungsten light is white, and is restricted to narrower bands of wavelengths by means of colored filters.



COLOR TRIANGLE of classical theory is shown in an early schematic form. Points of intersection of lines represent colors obtained by mixing spectral wavelengths in amounts proportional to distances from sides of triangle. Central point is equal mixture of primaries and is therefore white.

in the visible spectrum. And they have the miraculous ability to distinguish the longer record from the shorter, whatever the frequencies and the band-widths. Somehow they establish a fulcrum and divide the incoming carrier waves into longs and shorts around that point.

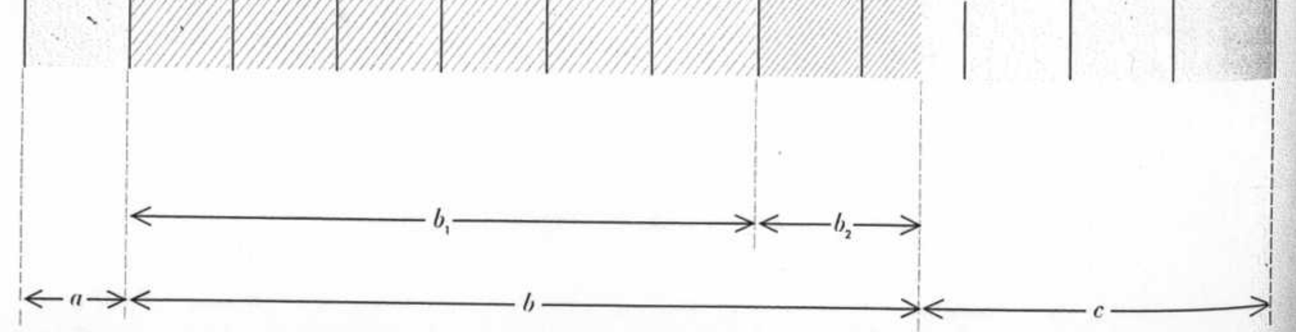
In our experiments we provide a single photograph averaging all the long wavelengths and a single photograph averaging all the short. What happens in the real world, where the eyes receive a continuous band of wavelengths? We are speculating about the possibility that these wavelengths register on the retina as a large number of individual color-separation "photographs," far more than the three that Maxwell thought necessary and far more than the two that we have shown can do so well. The eye-brain computer establishes a fulcrum wavelength; then it averages together all the photographs on the long side of the fulcrum and all those on the short side. The two averaged pictures are compared, as real photographic images are compared in accordance with our coordinate system.

Finally I should like to make clear that, although our experiments deal with two photographs and our coordinate system is two-dimensional, we have not been describing a two-color theory of vision. When we use a band of wavelengths for either or both of the records, we have light of many wavelengths coming from each point on the screen. And if classical three-color theory holds, it should describe the color of each of these points. This, as we have seen, it completely fails to do. It is true, however, that our experiments deal with two packages of information. We have demonstrated that the eye can do almost everything it needs to do with these two packages. The significance of what a third package will add is far from obvious. We are building a triple image-illuminating monochromator to find out.

A third picture may provide better information at the photographic level or an additional and useful interaction with the stimuli from two images. However, there is not a very big gap in the sensation scale to be filled by the third picture. In a given image a particular combination of two stimuli might not provide an electrically intense blue or a delicately yellowish green, but it is still likely to provide more than enough for the animal to live with. Nevertheless we do expect that the richness of many colors will be increased by the interplay of a third stimulus. Whatever we learn by adding a third picture, the visual process will remain an amazing one from the evolutionary point of view. Why has a system that can work so well with two packages of information evolved to work better with three? And who knows whether it will not work better still with four, or five or more?

What does the eye itself do in the everyday world of the full spectrum? Does it make only two averages? Or does it put to better use the new ability we have discovered—the ability to distinguish sharply between images at closely spaced wavelengths? Perhaps it creates many sets of averages instead of just two or three.

Even if more than two information channels are used, we feel that the big jump is obviously from one to two. Most of the capability of our eyes comes into play here. And whatever may be added by more channels, the basic concept will remain. Color in the natural image depends on the random interplay of longer and shorter wavelengths over the total visual field.



WAVELENGTH AND COLOR are independent of each other, except for the long-short relationship. This diagram shows the roles that various wavelengths can play. Those in the interval *a* can serve only as the short-record stimulus; those in *b* may be either long or short; those in *c* can only be long. If the wavelengths in b_1 are used as short-record stimuli, they will combine with a longer wavelength to produce the full gamut of color. If they are used as long-record stimuli, they will produce a more limited range. Wavelengths in b_2 will produce full color, serving as the stimuli for either the long record or for the short record. When both stimuli come from between 405 and 520 millimicrons, "short-wave reversal" occurs *(see color map on page 291)*.