THE USES OF COLOR

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One may approach the problem of designing maps from a common sense viewpoint and thereby produce useful and attractive maps. Maps so constructed will vary in usefulness and attractiveness with the experience, intelligence and aesthetic sense of the mapmaker. Although such differences are inevitable when human beings deal with any complicated real-life problem, the average quality of maps may be improved if scientific knowledge is brought to bear on the task. In the present instance a scientific understanding of the nature of the viewers of maps (human beings) can serve to enhance the quality of maps.

Maps, like graphs, printed texts, electronic displays and other communications channels are information transmitting devices. Maps summarize information in a way that is particularly convenient for human users. Thus, a human observer can learn about the distribution of unemployment across the continental United States by merely glancing at a well-constructed map. He could obtain the same information a bit more slowly by looking at a graph and a great deal more slowly by looking at a table of numerical data. The map, by virtue of its pictorial properties, allows the observer to process information in parallel and in rapid sequence and relate it quite directly to meaningful categories of knowledge, e.g., familiar geographical entities. Thus, in some sense a map is a broad bandwidth information transmitting device. However, as in the field of electronic communications, there is little point in transmitting a large amount of information per unit time if the receiver is incapable of handling it. While it may be possible to represent many different dimensions simultaneously in a single map, we can reach a limit beyond which the human mapreader will become confused. Thus, the scientific study of the human as an information processor is quite pertinent to the task of the mapmaker who wants to transmit as much information to the mapreader as can be conveniently handled. To do this he must take into account the amount of time that the reader has available to study the map, the way in which the information is to be represented, e.g., in alpha-numeric form or in terms of coded shapes, the legibility of the elements of the map, the purpose for which the map is intended, and so forth. My main focus in this talk is on color as a means for providing information in maps. Thus, color, as you all know, can be used to replace or supplement alpha-numeric symbols. It is obvious to all of us that such a use of color can have important effects on the rate at which information is communicated to the reader. There must, of course, be a trade-off between the value inhering in the use of color and the economics of color reproduction. I shall not deal here with the latter question but only with the idea that a better understanding of how the human being senses and uses color can enhance the effectiveness of the application of color in mapmaking.

EDITOR'S NOTE: Graphics accompanying the original presentation are not reproduced here.

INFORMATION PROCESSING AND RECALL

To see this in perspective let us first briefly review some basic ideas about the psychology of information processing. At one time it was widely believed that the human observer could store only three or four independent items for immediate recall after a brief exposure. Thus, if he were briefly shown a matrix of letters and then asked to recall them, the observer would be likely to report only three or four of the items correctly. However, as Sperling showed, if the observer were instructed to report on the items in only one of the rows of letters in the matrix he had just seen,then he could report on three or four of the items in the matrix. This result established that there is a storage of a great deal of visual information which the observer can scan after the exposure. By the time he reports on a few of the items in this stored image the image will fade, thus accounting for the fact that he seems to remember but three or four items.

Nowadays we believe that information retrieved from the stored visual image is placed in a buffer known as the short term memory. This is where you keep a phone number you had just looked up prior to making the call. As soon as it is dialed the number is quickly forgotten. There is also a long term memory in which rehearsed items are stored. None of what you have stored in long term memory is directly available to your awareness. It must first be called up and placed in the short term storage for you to be aware of it. For example, think of your home phone number. You were not aware of the number until you started to recite it to yourself. The item must be retrieved from long term store before you can use it.

All of these facts and many others were probably reviewed for you in the seminar on Map Reading and Perception. Unfortunately, most of the basic work done in this field of human information processing employed linguistic materials such as letters, numbers and words. In real life we are concerned with things that are less easily segregated into independent items. What are "items" or isolatable features of a woodland scene which is perceived as familiar years after seeing it but once? Also, not enough work has been done on the effects of purely physical attributes of items or stimuli on storage in short term memory. This is the place where the person actually initiates operations on information to solve problems, make interpretations, etc. Surely, some things are more salient and defineable to the perceiver than are others. These most salient things are more likely to be remembered and therefore used in conjunction with other things in interpreting the world. We do not know enough about the factors which affect saliency nor about the ways in which saliency affects information processing. Nevertheless, we do know a great deal about fundamental visual processes which can help us in making judgments as to the discriminability of things from each other. Surely, this discriminability plays a fundamental role in delineating objects and features of an environment for subsequent cognitive processing. Therefore, although we must await further developments in the rapidly growing field of information processing, it is still possible to discuss well known characteristics of the human observer, paying particular attention to his visual system, in order to define his ability to discriminate among things.

PERCEPTION OF COLOR

The biological mechanisms underlying our ability to perceive colors are similar in many respects to the mechanisms associated with the other sensory modalities. The problem for the organism is to transmit information which would permit it to discriminate among thousands of different colors by means of a very limited number of different kinds of receptors in the eye. Thus, any normal human observer can differentiate among thousands of different colors. There may be hundreds of different blues - some more or less greenish and others more or less purplish - and hundreds of different reds - ranging from orange to slightly bluish - and so forth. Each of these colors is qualitatively different from all of the other perceived colors. The eye has a finite number of different kinds of photoreceptor. How does it succeed in preserving information about fine difference in the wavelength of the stimulus despite the fact that there are a small number of photoreceptors? We now believe that the differences among colors are preserved even though there are only three different kinds of cone or color receptor in the eye.

Before discussing the three basic photoreceptors we must consider the color solid. This double pyramid is a summary or model of the various dimensions of color perception. Thus, the rim of the circle contains all of the hues ranging from red through orange and yellow to green and blue and, finally, purple. Purple differs from all the other colors because there is no single wavelength of light which would appear to have a purple color since it can be produced only by a mixture of red and blue lights. The hues on the very rim of the circle are considered to be pure colors -- i.e., fully saturated. If a particular color were impure or relatively desaturated by virtue of being mixed with white light, then it would be placed away from the rim within the color solid. A neutral gray patch is localized right on the central axis of the color sold since it has no hue. It is, as Newton said, the "middling" color of all the colors. Thus, saturation or degree of purity is represented by the distance of a color from the central axis. Shades and tints are located either above or below the color circle. Pink is placed above the circle. A very pale pink is located near the central axis and it fades into white as it approaches the upper vertex. Navy blue, on the other hand, is placed below the circle. This color can fade into black as it approaches the lower vertex. Thus, the color solid is a way in which to represent the dimensions of saturation (purity), hue and relative degree of "whiteness" of perceived hues. In addition to these three dimensions of color, i.e., hue, saturation and shade, we must add the fourth dimension of brilliance. A color of a particular hue and of a particular shade can have the same purity over a wide range of light levels. Turn on six more lamps to view a colored patch on a map and the color may appear to have the same attributes but nevertheless appear to be more brilliant. We shall ignore the fourth dimension of brilliance or brightness in this talk.

PHOTORECEPTORS

This color solid was known to the early workers in the field of vision. Its shape has been altered over time. An alternative model is shown in slide 2. Nevertheless, the basic idea of representing the dimensions of color perception in a single model is the same.

The great 19th century physicist James Clerk Maxwell showed that it is possible to match the appearance of any color by a mixture of no more than three spectral colors. The only constraint on this is that one of the three so-called primary colors could not be duplicated by a mixture of the other two colors. This very fundamental observation led Helmholtz to the conclusion that we do not need a special color receptor in the eye for each perceived hue. Thus, we do not need receptors specially designed for picking up red light, others for green light, still others for blue-green, yellow, orange and violet. We could get along nicely if we have but three kinds of receptors, one primarily sensitive to red light, another kind which responds primarily to green light and, finally, one sensitive to blue light. All of the colors could be represented by the relative amounts of activity in the neurons excited by these three kinds of basic color receptors.

One of the important correlates of color is the wavelength of light. It is well known that light of relatively short wavelength (about 460 nm) appears to be blue, light of 490 nm appears blue-green, of 510 nm green, and yellow at about 575 nm. Light of 600 nm appears orange and longer wavelength light appears red: A change of a few billionths of a meter in the wavelength of electromagnetic energy will cause a considerable shift in the quality of the perceived light.

Except for lasers, which emit nearly monochromatic light, and also light passed through finely tuned interference filters having a bandwidth of about 5 nm, most of the light we see contains a relatively broad band of wavelengths. A surface which appears to be green in color may reflect a continuous spectrum of light to the eye but with a predominant wavelength near 510 nm. All other wavelengths may be present but in different amounts. It is these differences in amount of energy at different wavelengths that determines the color of an isolated surface. I say "isolated" because effects of contrast between a surface and its surroundings can strongly influence the perceived color.

We now know that there are three kinds of photoreceptors similar to those I mentioned previously. One of these receptors will respond maximally to light from the "blue" portion of the spectrum. Thus, if light of 575 nm were to impinge on this receptor the pigment it contains would absorb fewer quanta of that light than it would of light of, say, 450 nm. Thus, blue light would be more likely to cause the "blue" or B photoreceptor to respond than would light of longer wavelength.

The pigment in the B photoreceptor is known as <u>Cyanolable</u> which means that it is the "blue catching" pigment. A second kind of photoreceptor contains a pigment known as <u>Chlorolabe</u> since these G cones contain a green catching pigment. Finally, the normal eye contains cones which respond primarily to red light (the R cones) and these contain a pigment called <u>Erythrolabe</u>. Rushton, who originated the terms cyanolabe, erythrolabe and chlorolabe succeeded in actually measuring the absorption characteristics of two of the pigments in the living human eye.

We have ample direct physiological and psychophysical evidence for the existence of all three photoreceptors.

We even have knowledge of some of the higher-order neural circuitry involved in color vision. Thus, it is known that the outputs of the R and G receptors impinge on common cells which take the difference between the two signals. This difference signal represents the color yellow, thereby confirming an idea proposed about a century ago by Hering.

COLOR MIXING

There are two ways in which to mix colors. In one way we simply add one light to another light by reflecting both colored lights off a screen. This is called additive color mixture. It is possible to take any given color produced by a complex of wavelengths and match it with some mixture of three monochromatic primaries. This mixture of the three monochromatic primaries can now be used interchangeably with the original complex color in other color mixtures even though their wavelength compositions may be entirely different. Such apparently equivalent colors are called matameric matches.

One variant on this method is to print tiny isolated dots of different colors next to each other. Since the eye cannot resolve the separation between the dots their colors are effectively added on the retina - thus producing additive color mixture.

A second kind of color mixture is called subtractive. An example of this is the mixture of blue and yellow paints or pigments to produce a green color. This occurs because the yellow portion of the spectrum of light reflected by the "yellow" pigment is absorbed by the "blue" pigment while the blue portion of the light reflected by the "blue" pigment is absorbed by the "yellow". Light of predominantly green wavelength (although somewhat muddy or desaturated) is left over thereby giving the mixture its green color. Additive mixture of blue and yellow lights, on the other hand, does not yield green. Such a mixture yields a neutral light if the yellow and blue lights are balanced in luminance. When out of balance then the resulting color will be that of the predominant element of the mixture, i.e., either a desaturated blue or a desaturated yellow.

All of these effects of color mixture are completely predictable from known scientific principles. I cannot communicate all of these principles to you in this short talk. However, I refer you to some of the texts cited in the bibliography for full details. The important point to be taken away is that we can specify any color completely. This can be done by determining the mixture of primaries which will yield that particular color. It is not even necessary to conduct empirical studies to discover the mixture of standard primaries which will yield the color. The average or ideal human eye has been studied extensively and tables exist which enable us to go from purely physical measurements of the wavelength composition of any color to the primaries which, when mixed in the proper proportions, will yield that color.

So far I have talked about the appearances of colors when they are viewed as isolated patches. A major effect is also produced by contrast between a patch and its surrounding. Thus, a grey patch seen on a red field will look greenish. In general, there is a tendency for a colored region to cause adjacent neutral regions of the visual field to take on the complementary hue. Some kinds of contrast are to be avoided in printed colors. When truly complementary colors are printed alongside each other a disconcerting effect known as "jitter" may take place, depending upon the wavelength composition of the illuminant and the luminances of the colors. Thus, yellow print on a blue background may appear to move as the eye scans the page.

COLOR FOR INFORMATION TRANSFER

Color is a useful dimension for the portrayal of information. Simple maps which use different levels of luminance to produce several different shades of grey can and have been used to show how some parameter varies with spatial position, e.g., five different shades of grey to represent five different levels of economic activity across some geographical region. Such maps can and have been improved by adding color differences to differences in greyness. In some cases such uses of color are redundant since they merely reflect the same information given by the different shades of grey. However, variations in hue may be superimposed on variations in greyness to convey information about some second independent dimension. We need some experiments to tell us how many different levels can be so represented on a map designed for a given purpose. For example, five different colors and five different shades of grey to reflect five different levels each of two independent parameters may not be useful for a lecturer using a map as a slide in a short talk. However, the same map may be useful to a student who takes time to study it. A dark grey superimposed on a yellow may yield a brownish color which could be hard to distinguish from an orange superimposed on a slightly lighter grey color. It is probably better to use colors which are widely separated on the color circle for such maps. Also, problems may arise if the two parameters are not independent but if they interact, as in the hypothetical example of a map showing unemployment rates together with consumption of certain goods where increases in unemployment may be correlated with decreases in consumption. We may not gain very much in such a case by using two dimensions such as color and shade of grey.

SUMMARY

I cannot do more than hint at the many things we vision scientists may be able to contribute to your endeavors. I would like to close, however, with one word of caution. One male in eight suffers to some degree with some kind of color deficiency. The most common form of color blindness is an inability to distinguish between red and green colors. We have learned a lot about color vision from the study of such deficiencies. For your purposes it would be well to avoid equally bright reds and greens as codes for differentiating places on a map. Blue-yellow deficiencies are much more rare. Such forms of color blindness are attributable to the lack of one of three kinds of cones. There are other kinds of deficiency which are attributable to the fact that one of the pigments of the cone-types may have abnormal spectral absorption properties. A patient study of these problems could allow you to take the more widespread deficiencies into account in designing your maps so that people will be able to read them and make appropriate discriminations despite their deficiencies.

In conclusion, we already know a great deal about the visual system. We know less about how to apply this knowledge to complicated real-life situations. However, it is easy to imagine experimental studies which would allow us to improve the use of the existing basic data.

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