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Kay, Paul

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COLOR PERCEPTION AND THE MEANINGS OF COLOR WORDS

Paul Kay
University of California, Berkeley

The relation between perception and meaning is hard to trace in any domain. I have been asked today to discuss the problems of identifying such connections in the domain of color. Color is an area in which our ignorance regarding the relation of perception and linguistic meaning is less than total; nonetheless you will not be surprised to learn that here, as elsewhere, there are more questions than answers. In the time available I will be able to do no more than sketch one view of the matter and so will probably present a clearer picture than is in fact warranted by current knowledge. In particular there will be little time to discuss the detailed empirical evidence that supports this view and no time to discuss alternative views.¹

I will begin by describing in lamentably oversimplified terms certain structures in the human visual system that give rise to the sensation of color. We will then see how these aspects of visual physiology can help us understand independent findings regarding the meanings of words for color in the world's languages. In particular, starting from the simple arithmetic of differential firing rates of certain individual types of cells in the visual system, we are able to build a model of the perceptual categorization of color that explains a good deal both about cross-linguistically universal features in color naming and about dimensions of difference among the classifications of color found in the languages of the world. Finally we will see how this model organizes certain systematic observations that have been made regarding regularities in the temporal evolution of the color classification systems of the world's languages.

Aspects of the Neurophysiology of Color Perception

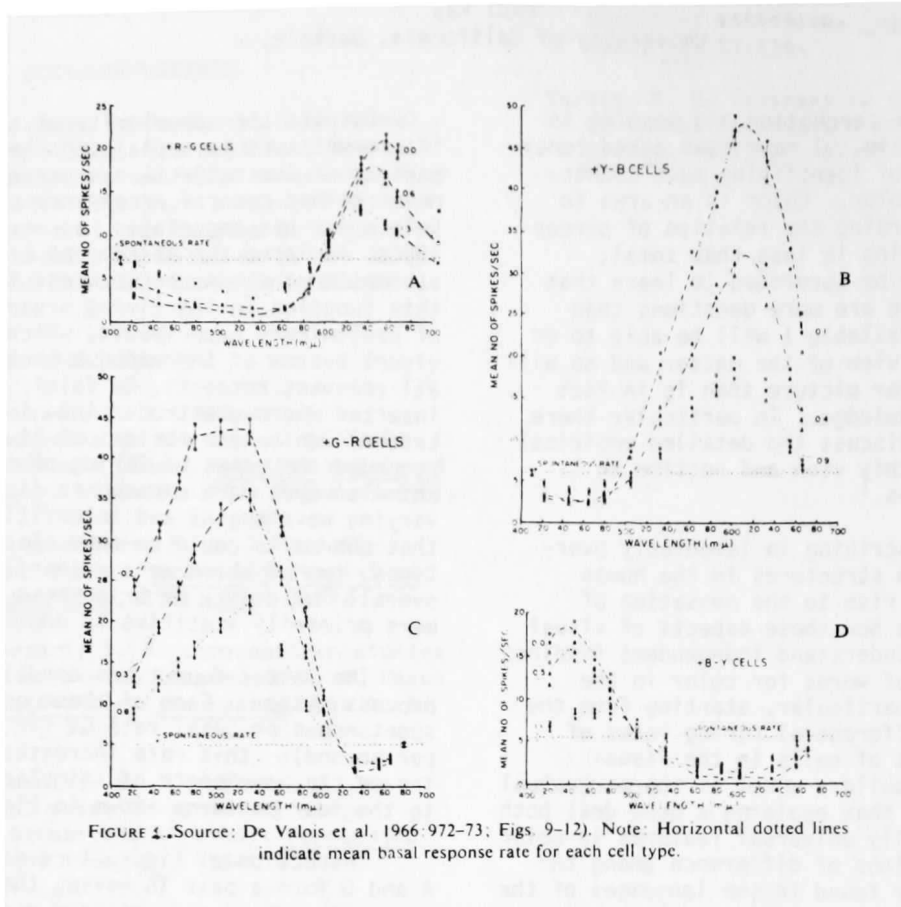
It is widely known that the retina contains three kinds of color receptors, i.e., cones. It is perhaps less generally known that at post-retinal but still peripheral levels of neural processing, information regarding dominant wavelength, or hue, is recoded from this three-channel system into a four-channel system, yielding the four fundamental hue sensations, blue, green, yellow, and red. In 1920 Ewald Hering (1968) postulated, on the basis of primarily introspective evidence, that such a system must exist. Hering noted further that subjectively there is no such thing as a mixture of green and red nor of blue and yellow--try to imagine what one could possibly mean by the locutions 'a reddish green' or 'a bluish yellow'. He therefore supposed that there must exist what he called two 'opponent processes' in the visual system, one red vs. green process and one yellow vs. blue process. At a given moment, each process has to be in exactly one of its named states; for example, at a certain time the red-green process might be in the red state and the yellow-blue process in the yellow state: this pairing of states would give rise to the sensation of orange. If one admits continuity to the model by allowing each of the four opponent states to operate at varying strengths, the relative strengths of the two states operative at a given moment will determine the precise shade that is subjectively experienced. In our example, the relative strengths of the red and yellow states will determine whether a reddish orange, a yellowish orange, or a relatively balanced or pure orange is experienced.

Despite the superiority of the Hering model over its competitors in explaining these and many other aspects of the subjective experience of color, it never gained general acceptance until Russell De Valois and his associates, as recently as the late 1960s, isolated the anatomical structures that accomplish the opponent-process function and monitored this function in the living organism. After a series of preliminary experiments, which established that the visual system of the macaque monkey is like man's in all relevant respects, De Valois and his co-workers inserted micro-electrodes into individual cells in the Lateral Geniculate Nuclei of live macaques and recorded the rates of firing of these cells while the animals' eyes were exposed to light of systematically varying wavelengths and intensities. It was found that LGN cells could be thus classified into six types, two of which were primarily sensitive to overall luminosity or brightness, and four of which were primarily sensitive to dominant wavelength or hue.

The latter four types constitute the opponent process system. Each of these opponent cells has a spontaneous or basal rate of firing (or about 6 spikes per second): this rate increases or decreases depending on the wavelength of stimulating light according to the four patterns shown in Figure 1.

Inspection of Figure 1 reveals that types of cell A and C form a pair in having the same crossover point between advanced and retarded rate of firing at about 605nm and also in having mirror image maxima and minima of firing rate at about 540nm and 640 nm. Cells of types A and C together constitute Hering's postulated red-green process: considering all cells of types A and C at once, we may take the sum of the absolute deviations from the basal rate of firing in the long wavelength region, that is above the crossover point, as signaling the strength of the red response. Similarly, the total absolute deviation from the basal firing rate below the crossover point represents the strength of the green response. In analogous fashion the type B and D cells together constitute the yellow-blue opponent process: the sum of absolute deviations above the crossover point is the total amount of yellow information or equivalently the strength of the yellow response, while below the crossover point the sum of absolute deviations represents the total blue response. Note that in a given stimulus condition, each opponent process must be in either one state or the other depending whether the wavelength of the stimulus is above or below the crossover point for that pair of types of cells.

At a given wavelength there are thus two families of possibilities. (1) If the visible wavelength is at one of the cross-over points, then one of the opponent systems is inert, e.g. at about 605nm the macaque's red-green system is quiescent; at this point all hue information is carried by the yellow-blue channel, which is in the yellow (longer wavelength) state; this is called the yellow unique hue point; all the organism sees at this wavelength is pure yellow. The blue, green, and red unique hue points are defined in the same way. (2) If the stimulus wavelength is not at a unique hue point, then exactly two of the four fundamental hue states are operative and the relative strengths of these two states determine the precise shade of perceived hue; for example in the region



between the yellow and green unique hue points the green state of the red-green system and the yellow state of the yellow-blue system are operative; the relative strengths of these response states determine whether a yellowish green, a greenish yellow, or a perfectly balanced chartreuse or lime is perceived.

One may, in sum, model this system as having quantitative outputs in four channels, RED, YELLOW, GREEN, BLUE, where at a given instant there are non-zero outputs in either (1) a single channel or (2) two adjacent channels (considering red and blue as also adjacent). From psycho-physical data Wooten (1970) has estimated the curves for humans comparable to those of Figure 1. Using these curves (not shown here) it is a straightforward matter to calculate for each channel of fundamental hue response (RED, YELLOW, GREEN, BLUE) the proportion of total hue response in that channel for each wavelength of visible light. Curves representing these calculations are shown in Figure 2. Being proportions, these functions necessarily have ordinates varying from zero to unity across the spectrum. It is therefore natural to interpret them as fuzzy sets, which interpretation is reflected by the ordinate of Figure 2 being labelled "Degree of Membership".

So far we have talked only about types of neural cells, their rates of firing, and certain functions composed of the firing rates of different classes of cells, but we have said nothing about the meanings of any words in natural languages. We are now prepared to make the initial connection: the curves labelled BLUE, GREEN, YELLOW, and RED in Figure 2 represent at one and the same time (1) the outputs of the fundamental hue-response categories as defined in terms of proportional output in the individual hue channel of the opponent process system, and also (2) the meanings of the ordinary English words blue, green, yellow, and red, along with their exact translations into many languages. Similarly, non-opponent fundamental response channels BLACK and WHITE, corresponding to the English words black and white (and their translations in many other languages), are defined by the two classes of brightness-sensitive cells discovered by De Valois and his associates, and these categories also may be modeled as fuzzy sets.

The Semantics of Color Words

We have seen that six English color words (and their translations into other languages that have exact translations of these words) can be given

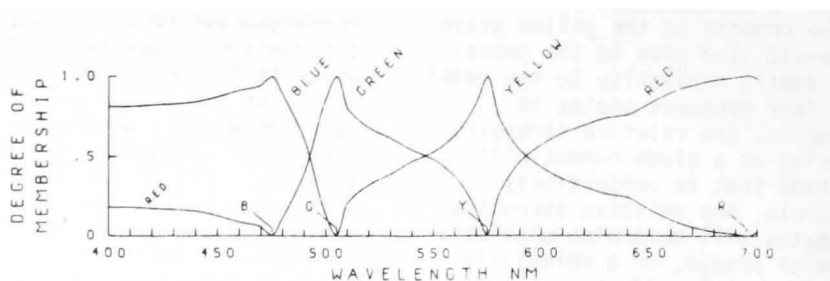


FIGURE 2.

neurophysiological definitions. For these six semantic categories, we have achieved a considerable rapprochement of semantics and perception. What can we say now about the perceptual basis of other color words in English and in other languages? In this investigation we will restrict our attention to what have come to be called 'basic' color words. In any language the basic color words form a natural set, and it is the comparison of the sets of basic color words across languages that has been found most fruitful in the cross-linguistic investigation of this semantic domain. In every language there is a small set of semantically simple words such that any color can be named with a member from this set. Members of this set are called the basic color words or basic color terms of the language. Several languages are known in which there are just two basic color terms. English has eleven; in addition to the six already discussed, which name the fundamental neural response categories, there are also brown, purple, pink, orange and grey. For many speakers of Russian, there are twelve basic color terms; Russian has a basic color term specifically for light blue, goluboy, along with the term for darker blue, sinyy.

For a long time it was believed by linguists and anthropologists that there were no constraints on the way the basic color terms of a language might divide the perceptual domain of color and hence no tendency for color words to be translatable across unrelated languages. Another way this idea was put was the claim that perception has no influence over color-naming in a language beyond setting the bounds of the visible spectrum. Thus in what was probably the most widely accepted linguistics textbook of the 1950s, H. A. Gleason said, "There is a continuous gradation of color from one end of the spectrum to the other. Yet an American describing it will list the hues as red, orange, yellow, green, blue, purple--or something of the kind. There is nothing inherent either in the spectrum or the human perception of it which would compel its division in this way" (1961:4). We now know that this is wrong and that all the basic color terms in all languages are based on the six fundamental response categories: the four of the opponent (i.e. hue) system and the two non-opponent (i.e. brightness) categories.

We have already noted that each of these six categories has a structure that invites its interpretation as a fuzzy set. There is strong additional motivation for the fuzzy set interpretation, namely that all the other basic color categories, either in English or in any of the other languages that have been investigated, may be defined in terms of simple Boolean functions of these fuzzy sets. For example, in many languages of the world, including the majority of Native American languages, there is a single word

that is used wherever an English speaker would use either the word green or the word blue. There is considerable experimental evidence indicating that this widespread basic color category (let us call it 'grue') is in fact the fuzzy union of the fundamental neural response categories GREEN and BLUE. For example, it has been found in a large number of languages that subjects asked to pick out from an array of color stimuli the best example of their category grue will not select something intermediate between green and blue such as we might call turquoise or aqua; rather, they will select either a focal green or a focal blue. Since the union of two fuzzy sets is defined as the maximum of the individual characteristic functions, this pre-theoretically surprising, but empirically robust, finding is predicted by the definition of the category 'grue' as the fuzzy union of GREEN and BLUE.

Berlin and Kay (1969) surveyed the basic color lexicons of ninety-eight languages and reported strong constraints on the semantics of basic color term systems. They also postulated a narrowly constrained evolutionary sequence through which basic color lexicons must pass as they add terms over time. That sequence, as reformulated by Kay and McDaniel (1978) about a decade later on the basis of a great deal of work by many investigators in the interim, is summarized in Figure 3.

A language with only two basic color terms has one which is the fuzzy union, 'WHITE or RED or YELLOW', and one which is the fuzzy union, 'BLACK or GREEN or BLUE'; these are conveniently glossed as 'light-warm' and 'dark-cool', respectively. When a language adds a third term, it does so by splitting the 'light-warm' term into a 'WHITE' term and a 'RED or YELLOW' (i.e. 'warm') term. At the next stage of development, either the 'dark-cool' term splits into 'BLACK' and 'GREEN or BLUE', that is 'cool', or the warm term splits into 'RED' and 'YELLOW' terms (see Stages IIIa and IIIb in Figure 3). At Stage IV, whatever possibility didn't occur at Stage III now occurs, so the language now has basic terms for the fuzzy categories 'WHITE', 'BLACK', 'RED', 'YELLOW', and 'GREEN or BLUE' (i.e. 'grue'). At Stage V, the 'grue' category is dissolved into its fundamental neural response components 'GREEN' and 'BLUE', and there is now one basic color term for each fundamental neural response category.

Up to here in the sequence, we have been considering two types of basic color categories, those that consist in unions of fundamental neural response categories and those that consist in the fundamental neural response categories themselves. Beyond evolutionary Stage V, basic color categories of a new kind are formed on the basis of the intersections of the fundamental categories. More precisely each of

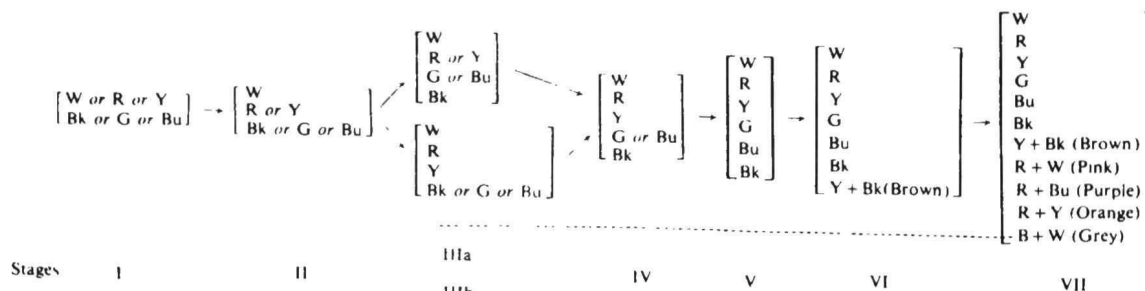


FIGURE 3

these later combinations of the fundamental categories consists in twice the fuzzy intersection of its constituent categories. For example, the fuzzy set orange is twice the intersection (minimum) of the fuzzy sets RED and YELLOW.²

It is not possible in the time available to discuss the empirical motivation for the formulation of these intersectional categories in terms of precisely twice the intersection of the constituent fuzzy categories (see Kay and McDaniel 1978:631-635; Mervis and Roth 1981). But the main points of the story so far should now be clear. Empirical semantic researches have revealed that, so far as we can tell at present, all the basic color categories of the languages of the world are based on the six fundamental neural response categories, whose structures are determined by the firing patterns of LGN (and other) cells in the visual pathway. Languages with fewer than six basic color terms have terms that encode categories composed of fuzzy unions of the fundamental categories. Languages that encode more basic categories than the six perceptually fundamental ones, encode categories based on the fuzzy intersections of the fundamental ones.

Furthermore, there appear to be quite narrow constraints on which of the logically possible Boolean combinations of the six fundamental response categories actually occur in the world's languages. For example, of the fifty-seven possible categories that might be formed by taking fuzzy unions of the six neurologically fundamental categories, only the four we have discussed ('light-warm', 'warm', 'dark-cool', and 'cool'--i.e. 'grue') occur in actual languages. Little is known by way of explanation of this fact, though it is perhaps worth recalling that Hering designated the colors white, red and yellow collectively as inherently arousing, and the colors black, green and blue as inherently non-arousing. Even more striking as an empirical generalization crying for theoretical explanation is the evolutionary sequence depicted in Figure 3. Why should the color lexicons of the world sort into just the handful of types permitted by this sequence and, above all, why should the temporal evolution of color terminology systems follow this particular, narrowly restricted course? Answers to these questions, as they are found, will deepen our understanding of the relation of perception and linguistic meaning in the domain of color.

Notes

1. This talk is, in effect, a highly compressed summary of Kay and McDaniel (1978), and the hearer or reader interested in pursuing the subject should consult that paper and the references cited there. McDaniel (1972) was the first to propose a perceptual explanation for the Berlin and Kay (1969) findings regarding semantic universals in terms of the opponent process model of color vision. Figures 1, 2, and 3 accompanying this text are respectively Figures 4, 6, and 13 of Kay and McDaniel.
2. In Figure 3, the '+' sign denotes the binary operation 'twice the fuzzy intersection'.

References

- Berlin, B., and Paul Kay. 1969. Basic color terms: their universality and evolution. Berkeley & Los Angeles: University of California Press.
- De Valois, R. L.; I. Abramov; and G. H. Jacobs. 1966. Analysis of response patterns of LGN cells. *Journal of the Optical Society of America* 56:966-77.
- _____, and G. H. Jacobs. 1968. Primate color vision. *Science* 162:533-40.
- Gleason, H. A. 1961. An introduction to descriptive linguistics. New York: Holt, Rinehart and Winston.
- Hering, Ewald. 1920. *Grundzuge der Lehre vom Lichtsinn*. Berlin: Springer. [English version: *Outlines of a theory of the light sense*. Translated by L. M. Hurvich & D. Jameson. Cambridge, MA: Harvard University Press, 1964.]
- Kay, Paul, and Chad K. McDaniel. 1978. The linguistic significance of the meanings of basic color terms. *Language* 54:610-646.
- Mervis, C. B., and E. M. Roth. 1981. The internal structure of basic and non-basic color categories. *Language* 57:383-405.
- Wooten, B. R. 1970. The effects of simultaneous and successive chromatic constraint on spectral hue. Doctoral dissertation, Brown University.