UNIFICATION OF LANGUAGE AND NEURAL STRUCTURE IN COLOR VISION

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1. INTRODUCTION

Neurophysiology and linguistics initially pressed different frontiers in the understanding of color and its perception. Advances in both fields have now brought them to a point of overlap with regard to possible physiological structures underlying perception and language (see review by Ratliff (1976)). On one hand, physiological theory traces color perception from initial stimulus in the retina to neural states of the brain, called opponent mechanisms, associated with color recognition.¹ On the other hand, the linguistic theories, concerned with the degree to which color lexicons exhibit cross-cultural variation versus similarity (linguistic universality), describe color classification with a hierarchical scheme of increasing vocabulary. These theories are based on the observation that all languages share some portion of a set of 11 basic color terms.

Several linguists (Zollinger 1976, Berlin & Kay 1969) have shown qualitative correspondence between their lexical color categories and opponent theories. On the basis of quantitative tests we show, both in principle and in practice, that linear opponent theories are unable to account for certain, apparently universal, linguistic patterns. However, a nonlinear coupled opponent theory in which each opponent channel exerts an inhibiting effect on the other brings linguistics and opponent theory into greater accord. We find that there are two major difficulties in refining and extending theories based on such interdisciplinary efforts. The first problem is a methodological one. The linguistic data that reflect how narrowly color names are defined and the data that describe variation in referential definition of color names has not been collected with great accuracy. The second problem is a theoretical one. Psychophysicists have failed to recognize the degree to which color naming varies cross culturally, as well as the degree to which

restrictions imposed on the range of color name responses affect the nature of the naming process.

In 1969 Berlin and Kay found evidence in color naming to contradict radical linguistic relativism which claims that each culture divides up the color continuum arbitrarily. Berlin and Kay discovered that the 98 languages they studied could be classified in terms of a seven stage hierarchy, as represented in Table 1.²

Table 1
Lexical stages of Berlin and Kay
(from Witkowski and Brown 1978)

$\left[\begin{array}{c} \text{Macro-} \\ \text{white} \\ \text{Macro-} \\ \text{black} \end{array} \right]$	$<$	$\left[\begin{array}{c} \text{Macro-} \\ \text{red} \end{array} \right]$	$<$	$\left[\begin{array}{c} \text{Grue*} \\ \text{or} \\ \text{yellow} \end{array} \right]$	$<$	$\left[\begin{array}{c} \text{Grue*} \\ \text{and} \\ \text{yellow} \end{array} \right]$	$<$	$\left[\begin{array}{c} \text{green} \\ \text{and} \\ \text{blue} \end{array} \right]$	$<$	$[\text{brown}]$	$<$	$\left[\begin{array}{c} \text{purple} \\ \text{pink} \\ \text{orange} \end{array} \right]$
I		II		III		IV		V		VI		VII
									grey			

* = green or blue

The color lexicon of a language of a given stage includes the color terms listed above the roman numeral that denotes the stage as well including all color terms that appear to the left. Color terms are mutually exclusive. The most widely agreed upon referents of the color terms of a given language are the "focal colors" for that language. The terms *Macro-white* and *Macro-black* correspond roughly to the warm-light and cool-dark colors respectively, *Macro-red* covers reds, purples, pinks, oranges and browns. As one moves to languages of higher stages new color terms enter and the range of the previous stage's color terms becomes more restricted. For example, the *Macro-red* of stage II includes reds, purples, pinks, oranges and browns while the *Macro-red* of stage VI includes only reds, purples, pinks and oranges. The *grue* of stage III is replaced by *green* and *blue* in stage IV.

The work of Berlin and Kay provided some of the earliest evidence in support of the existence of culturally independent linguistic patterns, that is, the existence of "language universals".³

The physiological opponent theory of color vision was first introduced by Hering (1964) in 1878 and quantified in the articles by Hurvich and Jameson (1955), Jameson and Hurvich (1955). Opponent theories postulate the existence of three channels, or mechanisms, for the encoding of color perception and specify their

relationships to the three cone types in the retina. Two of them, the opponent red-minus-green (R/G) and yellow-minus-blue (Y/B) mechanisms of hue perception, transmit either of two mutually exclusive signals. The third mechanism, V_λ , is nonopponent and simply responds to overall illumination. Cells of these types have been identified (DeValois 1966) in the lateral geniculate nucleus of the macaque monkey whose trichromatic color vision is indistinguishable from that of humans. By convention R and Y responses are positive while G and B are negative in arbitrary response units.

The crux of opponent theory is the linkage between the hypothetical opponent mechanisms and the cones. The sensitivity of each of the three cone classes to monochromatic stimuli of wavelength λ is characterized by functions $S(\lambda)$, $M(\lambda)$ and $L(\lambda)$. For the linear model this is given by Equation (1) and Fig. 1.

$$\begin{aligned}(R/G)_\lambda &= \alpha_1 L(\lambda) - \beta_1 M(\lambda) + \gamma_1 S(\lambda) \\ (Y/B)_\lambda &= -\alpha_2 L(\lambda) - \beta_2 M(\lambda) + \gamma_2 S(\lambda) \\ V_\lambda &= \alpha_3 L(\lambda) + \beta_3 M(\lambda)\end{aligned}\tag{1}$$

where α , β , $\gamma > 0$, of order one, are taken to be constants over the range of intensities of samples in our experiments (the luminance ratio of pure focal red to pure focal green, as described below, was about 3 to 1).

Monochromatic stimuli at the balance points of one opponent mechanism, that stimulate only the other mechanism as can be seen in Fig. 1, are called unique hues. Monochromatic stimuli exist for positive and negative Y/B and for negative R/G but not for positive R/G .

The accuracy of the S , M and L curves is uncertain due to the difficulty of isolating human cone pigments. The forms used here⁴ have been deduced through the use of Dartnall's principle (Dartnall (1953)) and the visual properties of iodopsin.⁵ This principle asserts that the photopigments of different species have sensitivity functions of approximately the same shape, the principal difference being the position of their maxima. In vivo retinal densitometry⁶ and microspectrophotometry⁷ used to determine human foveal sensitivity support this assumption despite difficulties in isolating different absorbers.⁸

Fig. 1. *Linear opponent mechanism's response to equal energy spectral stimuli, (arbitrary units)*

The first implication of linearity is the constancy of hues under scalar multiplication of stimuli intensities, as in

$$R/G(t[\lambda_1 + \lambda_2 + \dots]) = t\{R/G(\lambda_1 + \lambda_2 + \dots)\}$$

for any t a positive real number.

It is well known that this form of linearity fails under extenuating circumstances. When monochromatic stimuli are shown at intensities varying over factors of $3 \log_{10}$ the clearly perceptible hue shifts are known as the Bezold—Brucke effect.

The second aspect of linearity, with which we are more concerned, is the additivity exemplified by $R/G(\lambda_1 + \lambda_2) = R/G(\lambda_1) + R/G(\lambda_2)$. This means that when two monochromatic stimuli are superimposed the net opponent response is the sum of the two mechanisms separately. Multiplicative linearity is a special case of additive linearity for $\lambda_1 = \lambda_2$.

General statements of the additive character of linear theories, called Grassmann's laws, have been axiomatized by Krantz (1975a, 1975b). In particular linear theories predict that a suitable mixture

of maximal positive R/G (or Y/B) and negative R/G (or Y/B) superimpose to leave both R/G and Y/B mechanisms in a neutral state.

It is possible, since we mix stimuli of different intensities, that our observations could be better matched by a theory linear in the response functions with intensity dependent coefficients. However theories of this sort that have been proposed do not have closed form expressions for the coefficients (that is do not have α_i as a function of intensity and wavelength), and further indicate that these parameters exhibit small variations, on the order of 5%, over the $5 \log_{10}$ mL luminance ratios⁹ encountered here. Therefore the only type of linear theories we consider are those in which the coefficients α_i are constants.¹⁰

2. THE LINGUISTIC EXPERIMENT

Our objective is to determine the correlation between the cross cultural linguistic labels *red*, *green*, *blue*, and *yellow* and the opponent theoretical unique hues red, green, blue, and yellow. Two comparisons are made. First we examine the degree to which these linguistically determined focal colors stimulate one of the two opponent mechanisms. This is a computational test that only requires the reflectance spectra of the focal colors and the response coefficients α_i , β_i and γ_i for $i = 1, 2$. Second we perform linguistic tests to determine whether the focal colors add according to linear theory. We look for combinations of focal red with focal green and focal blue with focal yellow that cause opponent mechanisms to cancel. The cancellation of the opponent mechanisms is signaled by the subjects labelling such stimuli as achromatic. Before we discuss the details of our method we examine the role of culture and language in psychophysics.

Any psychophysical experiment in which a subject's task is based on their own conception of color inexorably admits cultural variation. (Here Zollinger (1976) has shown that in different modern languages, color terms commonly translated as equivalent actually exhibit small differences in referential meaning.) Physiological theories commonly ascribe structural reality to linguistic categories¹¹ and assume that cultural deviations are smaller than experimental errors. Furthermore, the perceptual report is often distorted by restricting a subject's response to categories whose applicability

reflects the experimenter's own cultural bias. Using a measure called linguistic consensus, a measure which avoids the issue of what different subjects actually mean when they use a color label, we attempt to minimize these distortions.

Past psychophysical work on color naming that has investigated the correlation between stimuli and color names has proceeded on the assumption that color names correctly represent spectral colors. For this reason subject response has been limited to a set of basic color names. However, such an approach is plagued by several difficulties. The first is the issue of whether different subjects interpret color names to mean the same thing. For example, how does the definition of blue and green differ among subjects? Specifically, take the case of the unique yellow spectral hue which can be determined to within a couple of nm for a given subject; yet the spread of the means of such settings across a group of normal subjects can cover 10 nm.¹² Some of this variation is due to different opinions of what *yellow* describes. The second problem is that of translating basic color terms into other languages. Color terms in even closely related languages, like French and English, do not refer to exactly the same things. The unique hues in English (*red*, *yellow*, *green* and *blue*), will not be quite the same as those obtained according to native French speakers (corresponding to *rouge*, *jaune*, *verte* and *bleu*, Zollinger (1976)). For less closely related languages the problem is more serious. Consider the determination of unique hues using subjects who speak a language that fits into one of the lower stages in the Berlin and Kay scale — here not all the terms *red*, *green*, *yellow* and *blue* will have equivalent counterparts. In a stage IV language like Vietnamese, unique blue and unique green can not be determined because the language labels both blues and greens with a single collective term; given the label *grue* in English. (This does not mean that the language has no *referential* terms distinguishing blues from greens, but that such terms are not as basic¹³ as the *grue* label, and because the English labels *blue* and *green* are basic, they are not equivalent to these referential terms). Thus the use of particular color names to determine unique hues makes the physiological theory language dependent.

Psychophysical experiments often assume that colors and color names have a context independent meaning. While color perception is affected by boundary fields and adaptation, color perception is

assumed to be independent of whatever thoughts may exist concurrently in the mind of the observer. On this basis it is expected that psychophysical experiments test perception independent from recognition. However the process of naming objects involves both perception and interpretation. When investigating the extent to which interlinguistic naming patterns are due to common physiological structures we must recognize that naming is more than a perceptual process, it is both a process of recognition and categorization.¹⁴ We must be able to distinguish the perceptual aspect of color naming from the messages conveyed in the color terms themselves. That is, we must separate the "how" properties of language from its "what" properties.¹⁵

The important question is whether or not a means of using color names can be found that distinguishes the perceptual from the contextual part of the color label. To underline the nature of the problem consider the example of the color label *green*. It is difficult for an untrained person to distinguish a best green from a sample set of many green-hued colors. Yet to the same person a leaf or a blade of grass is unequivocally green. Let us assume, as an oversimplified case, that subjects have been taught to think of green as a rather broad label referring to the color of chlorophyll laden plants. Then on what basis could it be claimed that the green that is identified in the lab is the result of a unique perceptual state that is intrinsic, physiologically determined and contextually independent?

We present a twofold answer to this question. First, we claim that the degree to which a color is referentially well defined is proportional to the number of subjects that choose it as a label for a given stimulus. In the case of green, for instance, if a particular sample is given the label *green* much more frequently than it is given labels like *azure*, *lime*, or *emerald* then that sample is particularly representative of the word *green*. Thus, when we determine the focality of a sample color, that is the degree to which it represents a basic color term, we must admit alternative and less common labels. The second part of our answer to the question of how to distinguish the contextual from the perceptual meaning of color terms is to average over different languages. If there is a perceptual component to color labeling then it should survive in different languages while contextual effects should not. As reasonable as this may seem it cannot be put into practice until we can translate

color labels among different languages. The problem of translation is obviated by collecting data in a language independent manner.

Return to the project at hand. Our first test is to check if the hue coefficients of linear opponent theory support the linguistic salience of focal colors. The colors we use were determined from Berlin and Kay's original work. Berlin and Kay presented subjects with an array of 320 Munsell colors of equally spaced hues at 8 levels of brightness, all at maximal saturation, plus a linear array of nine neutral hued chips spanning the greys from white to black. Each informant was asked to spot the best representative of each of their color terms. That color which best represents a color term for a given language is called a "focal color" for that language. The geometric centers¹⁶ of these distributions (that is the averages over the language-specific focal colors), are called "generalized focal colors".¹⁷ Opponent mechanism responses to these colors are computed and discussed in the section "Predictions of the Opponent Theories".

Our second test proceeds as follows. Assuming that the identity of linguistic focal colors is due to the existence of linear perceptual mechanisms, this linearity should be reflected in naming experiments. We expect some mixture of opponent focal colors to be marked by the occurrence of complete opponent cancellation. The cancellatory mixture color should be marked by a color label signifying achromaticity.

Let us go to the linguistic methodology used to measure language independent focality. In order to measure the degree to which different sample colors are representative of focal colors we must allow a range of response that includes nonfocal labels. To do this in a language independent way requires that no restriction whatsoever be put on the character of subject response. In our tests subjects were shown an additive mixture of focal colors and asked to name the color of the sample. However, because the absence of any naming restriction resulted in too large a range of response we imposed the following fairly general restrictions. The subject's responses must come from their familiar vocabulary of color names (no spontaneously invented names), and the response must be only one word: the name of an object, the name of a color, or the hyphenated combination of two color names (like *blue-green*). The results are then tabulated according to a technique called linguistic consensus, introduced by Lenneberg (1953).

The consensus measure is defined as follows. Consider an experiment in which one presents the same stimulus to different subjects. The number of times each particular response occurs, divided by the total number of responses, is the relative response frequency. The response that is most frequent is called the modal response; the frequency of the modal response is called the consensus. By plotting the consensus values for a set of stimuli, say a sequence of colors from "pure" yellow through orange to "pure" red, one defines a consensus curve. Using this method we are able to treat the response categories as unimportant. The names of the response categories need not even be recorded.

A peak in the consensus curve indicates a stimulus that has particularly widely agreed upon name, a property indicative of focal colors. However one must exercise some care in interpreting consensus results as they are sensitive to the order of appearance of, and the range of variation between, different stimuli. For example, consider a simple naming experiment in which various hues of blue are shown, subjects use a wide range of labels in their reports to reflect their own processes of discrimination. On the other hand, when the same set of blues is shown interspersed with colors of widely varying hues the subject's reports draw less distinctions between the hues of blue than in the previous test. More of the bluish samples are given the simple label "blue" in this second test than in the first test, obviously affecting the consensus results. Thus consensus values vary with experiment. However the position of the consensus peaks is expected to be constant.

3. METHODS

In a first series of tests 30 naive, native English speaking subjects reporting normal color vision were presented with a random sequence of 19 additive color mixtures spanning the focal red to green and focal yellow to blue. Our focal red, green, yellow and blue¹⁸ (*R*, *G*, *Y* and *B*), have Munsell notation 5*R* 4.0/14.0, 7.6*G* 5.0/9.9, 2.4*Y* 8.0/15.5, 2.5*PB* 5.0/11.9. Also included was a combination sample of 12.44% blue, 32.17% red and 55.39% green that was constructed by 10 of the subjects on a previous test to be that mixture of these three colors with the most achromatic appearance.

Optical mixing was achieved by spinning 4", interlaced disks on a Maxwell color wheel, illuminated by two 60 watt sources (CIE illuminant A, $\sim 2800^\circ\text{K}$), subtending 3° of the subjects vision against a background painted black. The luminous excitance of a white sample was 2700 lm. m.^{-2} . Subjects were dark adapted for 5 minutes before and 30 seconds between viewing samples. Because our priority was accurate identification we allowed subjects to view samples for as long as they needed which was usually less than a minute.

Subjects were instructed to give a one word description that most accurately described the sample. These descriptions were to come from their familiar color vocabulary and could either be the name of an object, a color name or a hyphenated combination of two color names (like *blue-green*). Reports that used the same compound names but differed in their order were considered to be different descriptions. Subjects were also allowed to add either of the adjectives light or dark as many subjects felt this qualifier was necessary for linguistic categorization. But as we are only interested in hue differences (as opposed to value or saturation),

Fig. 2. Consensus values recorded for the two color transitions: a) focal red to green, b) focal yellow to blue. Dashed line is the consensus result of considering the labels white, grey and snow equivalent

and these words are not considered markers of different categories they are ignored in the analysis.

In order to obtain a measure of uncertainty in the experiment the responses were divided into three groups of 10 subjects. Following Lenneberg the consensus, $C(s)$, was calculated for a stimulus s as the ratio of the largest number of identical responses minus one to the total number of responses minus one. $C(s) = 0$ if no two people agree. Each group yielded one consensus point for each color mixture and the standard deviation is calculated as a measure of linguistic variation. In Figs 2 (a) and (b) the ranges are plotted with straight line interpolations connecting average consensus values. In the transition between Y and B , Fig. 2 (b), the result of considering the labels *white*, *grey* and *snow* equivalent, on the basis that they all connote achromaticity, is plotted as a dashed line.

4. PREDICTIONS OF THE OPPONENT THEORIES

Linear equations for the $R|G$ and $Y|B$ systems, Equation (1), are obtained from the data of Werner and Wooten (1979). They calculated parameters for each of three subjects by empirically fitting the undetermined coefficients α_i , β_i and γ_i to psychophysical tests of the chromatic appearance of spectral stimuli (see appendix). We use the results they obtained for their three subjects to create an envelope bounding the limits of possible response functions. Our response functions were then chosen to lie within these bounds while optimizing the agreement between opponent predictions and our linguistic observations. Optimization was determined on the following grounds. First, the calculated response functions were to support as much as possible the hypothesis that focal colors were extremal stimulants of only one of the chromatic response mechanisms. Second, the coefficients were to also support the hypothesis of linearity. A number of response curves were generated and compared with experiment, as is discussed at greater length in the next section. The set of coefficients which went the farthest in meeting the above criteria is given by equation (2).

$$\begin{aligned}\alpha_1 &= .43, & \beta_1 &= 3.75, & \gamma_1 &= 2.41, \\ \alpha_2 &= 2.83, & \beta_2 &= .29, & \gamma_2 &= .79, \\ \alpha_3 &= .6, & \beta_3 &= .4.\end{aligned}\tag{2}$$

α_3 and β_3 are quoted from Ingling and Tsou (1977). To compute the total response for each cone T_i we used an incident Planckian spectrum $E(\lambda)$, the reflectance of each mixture color:¹⁹ $R_1(\lambda) + R_2(\lambda)$, and the sensitivity functions for each cone²⁰ $S_i(\lambda)$ and integrated over frequencies.

$$T_i = \int E(R_1 + R_2) S_i d\lambda$$

Multiplying total cone responses by the coefficients of equation (2) and adding according to equation (1) gives the opponent mechanism responses to mixtures of focal colors. Hue coefficients h_{rg} and h_{yb} are defined as the ratio of a mechanism's response to the total response of all three. For example:

$$h_{rg} = \frac{R|G}{R|G + B|Y + V}$$

The linguistic consensus is predicted to be high when one mechanism greatly dominates the others. This occurs when one hue coefficient is much larger than the other. The dominance of the V mechanism, which occurs when both h_{rg} and h_{yb} are small, predicts that stimuli will appear achromatic. The results are plotted in Figs 3 (a) and (b). Symbols mark predicted values at experimentally tested color combinations.

Nonlinear $Y|B$ mechanisms, developed as empirical improvements upon the linear theory, constructed by Werner and Wooten (1979) and Larimer et al. (1975a, 1975b) using different methods, are given by

$$Y|B_\lambda = -2.97 S(\lambda) + |1.16 L(\lambda) - .07 M(\lambda)|^{.142} \quad (3)$$

and by

$$Y|B_\lambda = -2.56 S(\lambda) + 1.02 M(\lambda) + \Delta(0.6) |L(\lambda) - M(\lambda)|^2 \quad (4)$$

respectively. Where $\Delta = \pm 1$ according to $(L - M) \geq 0$. These coefficients, again chosen from coefficients Werner and Wooten fitted to subject data, optimize agreement with Figs 2 (a) and (b). For these computations $Y|B(\lambda)$ was determined at 10 nm intervals and then numerical integrated using Simpson's rule. However, the hue coefficients are not graphed in either case because, even at best, they fit observations much more poorly than the results of the linear theory.

Fig. 3. Hue coefficients predicted by the linear and inhibition models for the two color transitions

Finally we used an empirical model coupling the linear responses $Y|B$ and $R|G$ (given by Equation (1)), according to Equation (5), which we constructed in analogy with the lateral inhibition theory of Hartline and Ratliff (1957). Their direct observations of the visual receptors of the horseshoe crab, *Limulus*, led them to propose that a single receptor's response is inhibited by the stimulation of its neighbors. Their theory of brightness perception is basic to the understanding of boundary enhancement in mammalian vision.

$$y|b = (Y|B) \exp(-.06(R|G)) \quad (5)$$

$$r|g = (R|G) \exp(-.09(Y|B))$$

For a heuristic derivation of Equation (5) consider a cell, excited in proportion to a linear $Y|B$ input, that is spherically surrounded by other cells that are excited in proportion to a linear $R|G$ input. Assume the response of the first cell is damped by the activity of each of its $(R|G)$ -type neighbors at distances d_i by a factor

$[1 - \gamma |(R|G)/(d_i)^2|]$ (the same picture can be developed in two dimensions if $1/(d_i)^2$ is replaced by $1/d_i$). If $R|G$ cells are a unit distance apart, then a spherical shell of unit thickness and radius d_i contains about $N_i = 2(d_i)^2$ inhibiting $R|G$ cells. The product of all inhibitive effects, $D_{R|G}$, out to a distance of, say, $d_m = 10$ intercellular distance is:

$$D_{R|G} = \prod_{i=1}^{10} \left(1 - \frac{2\gamma}{N_i} |(R|G)| \right)^{N_i},$$

$$\sim \exp(-2\gamma |(R|G)|),$$

γ is chosen in conjunction with the values of $|(R|G)|$ and $|(Y|B)|$, computed with the linear model on the basis of our samples, so that $2\gamma |(R|G)| \leq .2$, $2\gamma |(Y|B)| \leq (.1)$. By assuming the number of nearest neighbor cells is greater than or equal to 10, the exponent form becomes a good approximation. The hue coefficients are shown in Figs 3 (a) and (b).

From this development it can be seen that the response x of one mechanism reduces the response of the other by a factor $D(x) \leq 1$, the 'effectiveness' (response of x divided by the factor by which it is reduced: $|x|/D(x)$), of this inhibition grows exponentially the larger that activity is. The important result is that differences in the hue coefficients are enhanced when both mechanisms are active. Referring to the original methods of Hurvich and Jameson for determining opponent response (see below), this means that if it takes 2 units of unique blue to eliminate the perception of yellow in the long wavelength end of the spectrum and 20 units of blue to do the same thing at middle wavelengths, these two sets of units are not perceptually identical, i.e. a unit of positive $Y|B$ at the long wavelengths has less perceptual effect due to the presence of red than it does near 580 nm where either red or green are only slightly evident.

5. COMPARISON OF THEORIES WITH EXPERIMENT

Ideally we would like to have a physiological theory that determines what linguistic responses will follow from given visual stimuli, however there does not exist any such detailed relation between hue coefficients and consensus response. Since some kind of theoretical relationship is necessary for the interpretation of our

consensus data, we will apply the following simple model consisting of two assumptions. First, that the exclusive stimulation of one or the other opponent mechanism results in the labeling of such stimuli with a focal color label and from this it follows that such stimuli should correspond to consensus peaks. Second, that the lack of stimulation of either opponent mechanism also results in the stimulus being given a focal label and consequently a consensus peak will again result. We do not go so far as to relate the actual percentage values of consensus with the percentage values of the hue coefficients.

According to this model, pure focal colors should elicit extremal consensus values as well as inducing extremal response in one of the hue mechanisms while leaving the other one inactive. Mixture colors that result in complete opponent cancellation (both hue coefficients zero), should also correspond to observed consensus peaks.

Our first observation is made entirely on the basis of the consensus information contained in Fig. 2 (a) and (b). If we believe the linguistic focal colors are the correct referents for their categories then the cancellation failure of focal red and green, evident from the lack of consensus along the transition, implies linear theories of opponent vision are incorrect. That is, the response functions of linear theory are not directly related to the categories of color naming.

The linguistic evidence alone indicates the cancellation of Y with B does not excite the $R|G$ mechanism, from which it follows that the $R|G$ system behaves linearly. The absence of a consensus peak in the R to G transition indicates the failure of these focals to cancel each other. However, the mixture ratio $R(32.2\%)$, $G(55.4\%)$, $B(12.44\%)$ did elicit 66% consensus which indicates that the appearance of stimuli in the R to G transition lacks this B component, i.e. has too much Y component to give an achromatic consensus. To get a quantitative measure of the amount of Y that is effectively present consider the achromatic point in the Y to B transition where it takes 41 parts Y to cancel 59 parts B . Then, from the $R:G:B$ achromatic combination above, the combination $R(32.2\%) : G(55.4\%) : X(12.44\%)$, where X is arbitrary, is equal to $Y(8.6\%) : g(79.0\%) : X(12.44\%)$, where the grey, (g), component is determined from the normalization condition that the components must sum to 100%. From the perceptual equation,

$$B(12.44\%) : R(32.2\%) : G(55.4\%) = B(12.4\%) : Y(8.6\%) : g(79\%),$$

we obtain,

$$R(37.0\%) : G(63.0\%) = Y(9.9\%) : g(90.2\%).$$

The grey that appears in this equation is a dark grey because the reflectance of both R and G is low.

Despite this evidence that the $R(37\%) : G(63\%)$ point is equivalent to a desaturated pure Y sample there is no significant consensus peak in Fig. 2(a). This reflects the small degree to which weak tints, tones and shades²¹ provide linguistic markers in English.

Note the trend in which the range of response varies directly with the consensus. We know of no previous observation or linguistic explanation of this.

The failure of R and G to show complementarity (as suggested by the work of Hering²²), is further substantiated by the work of Dimmick and Hubbard (1939a, 1939b). They found the complement of unique (non-monochromatic) red was a blue-green at 494 nm (unique blue: 475 nm, unique green: 515 nm), implying non-cancellation of unique red and unique green.

Turning to the calculations shown in Figs 3 (a) and (b), first consider the hue coefficients for the generalized focal colors alone. For purposes of comparison define a measure of hue predominance for hue coefficients x and y as $p(x, y)$ ranging from 0, when $x = y$, to 1 when x or $y = 0$.

$$p(x, y) = \frac{||x| - |y||}{(|x|, |y|)_{\max}}$$

where $(|x|, |y|)_{\max}$ equals whichever hue coefficient has greater absolute value. Predominance values for R , G , Y and B are plotted in Table 2.

Table 2.

Predominance values computed for the generalized focal color samples

$p(h_{rg}, h_{yb})$	Color			
	R	G	Y	B
Theory linear, (1)	57	94	50	28
Inhibited, (4)	76	98	90	52

It is evident that only focal green is a candidate as an extremal exclusive stimulant according to the linear theory of Equation (1). The inhibition theory provides substantial improvement by yielding uniformly higher dominance values that are more consistent with the interpretation of generalized focal colors as extremal exclusive stimulants. This is done without affecting the position of the achromatic points predicted by the linear theory.

Addressing the behavior of the hue coefficients across transitions, it appears that both the linear and the inhibition models are in approximate agreement with experiment in predicting equilibrium in both $R|G$ and $Y|B$ mechanisms at nearby points. Both theories predict a very desaturated hue along the Y to B transition between the ratios $35Y : 65B$ and $25Y : 75B$ compared with the observed consensus achromaticity peak at $38Y : 62B$ ($\pm 6Y : \mp 6B$, the estimated half width at $3/4$ maximum²³ of the achromatic consensus peak of Fig. 2 (b)). The appearance of a weak yellow is also predicted in the transition from 100% R to 100% G becoming unique at $32R : 68G$ versus the observed value of $34R : 66G$ as implied by a minor peak not clearly discernable within the bounds of linguistic variance. In particular the linear theory predicts sample B to have a very low ratio of $Y|B$ to $R|G$ response that disagrees with the high consensus value observed. While the inhibition theory again does somewhat better it still falls short of giving the predominance value that occurs for the other focals.

6. CONCLUSION

Determining the degree to which physiological mechanisms underlie linguistic focality poses an important challenge to color science. Yet it brings us into an area of particular difficulty for precise measurement because of the combination of individual physiological, linguistic and cultural variables. The definition of focality for a given language requires the reports of many individuals and as such focal colors represent an average over differences in individual physiology. The generalized focal colors, which have been used here, involve yet another layer of uncertainty as they represent an average over cultural variations, which underlies differences in the language-specific focal colors.

While it is not clear that any single physiological theory, representing an average observer, will satisfactorily match all consensus

patterns, we have shown that such a nonlinear model does generate response curves that are in reasonable agreement, at least with respect to the R to G and Y to B transitions. The following important issues remain to be resolved. To what extent will an improvement in the location of generalized focal colors raise the weak consensus observed for R and G and the low hue predominance predicted for B ? Will the extension of these experiments to include different languages and the generation of generalized consensus curves bring consensus results into closer correspondence with physiological predictions? And finally, can different average opponent response mechanisms raise hue predominance for the focals and predict the color mixture ratios that yield achromatic consensus peaks?

All of these issues require a refined notion of focality. The Berlin and Kay results are based on the reports of few informants from each language,²⁴ whereas the precise location of generalized focal colors requires many informants from each of many languages. While more information has since been gathered (Witkowski & Brown 1977) no one has attempted to reproduce the Berlin and Kay results to a higher degree of accuracy.

We need a language non-specific method for determining opponent response mechanisms (such as one that does not require subjects to tune a monochromator to a *green* that has no traces of *yellow* or *blue*). Such a method would enable us to define hue coefficients more objectively and we would be on firmer ground when making comparisons with the generalized focal color consensus curves. Results are needed at a language specific level as well as an individual level where individual definitions of focality could be compared with individually determined response curves.

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7. APPENDIX: SPECTRAL CHROMATICITY

In the original construction of the opponent theories (1) and (3), unique colors were first determined by asking subjects to tune a monochromator to give the best *green*, *yellow* and *blue*. Cancel-

lation experiments were then performed in which the spectrum was divided into steps and at each step the subjects admixed a unique hue to cancel their impression of *red*, *green*, *blue* or *yellow*. A long wavelength red was chosen to cancel the perception of *green*. Such a choice is acceptable because even though the red is not unique its yellow component can be accounted for and subtracted.

Although we expect the predictions of the linear theory (1) to match the colors of the spectrum, as this was the basis of its construction, what the results will be for the coupled theory (5) are not obvious. It is tested and compared with (1) using the data of Boynton et al. (1964) on color naming of monochromatic stimuli.

Fig. 4. Naming data, (Boynton et al. 1964), and hue coefficients for spectral stimuli

Their object was to show that accurate, reproducible results could be obtained by color naming "provided that a suitable measurement technique is used and the relevant parameters are well controlled". While their work allowed for a wider than usual range of responses it does not test universality or innateness as we have discussed in the previous sections because of its still restrictive and language specific nature. However, it serves our purposes for the following comparison.

The theoretical computations of the previous section were repeated for models (1) and (5) using monochromatic stimuli. For consistency the intensity of this hypothetical equal energy spectrum of stimuli was scaled so that extremal opponent responses were of the same magnitude as for the focal colors. As a result these extremal responses (according to (1)), of the spectral colors differed from those of the focal colors on the average by a factor of 2. (at the most by 4.6 in the case of the more excitatory focal yellow). We return to the usual definition of hue coefficients for mechanism x as the ratio of $|x|$ to the sum of the two mechanism's responses (before the brightness system response was included in the total response). These results, along with the naming data for a single subject from Boynton et al., are plotted in Fig. 4 (a) and (b).

These spectral naming results provide a second, independent test of these two theories. While their overall qualitative agreement is apparent, a small yellow shoulder at 520 nm is predicted by the linear theory but not by ours. Considering the hue coefficients for the long wavelengths the predictions of the inhibition theory show better correspondence with the naming data than does the linear theory. However, to base distinctions on differences of this scale requires some discussion of the grounds for comparison. First of all, the models represent an average observer while the data is from a single subject. Secondly, the experiment measures the pertinence of certain terms as spectral descriptions under somewhat forced conditions.²⁵ For instance a stimulus that fits neither of two available categories would tend to elicit both responses equally, but it does not necessarily follow that two mechanisms are equally active. In fact, a subsequent investigation²⁶ of the 530 to 620 nm region, in which subjects estimated the degree of red, green, yellow, blue or orange present on a scale of 1 to 100, shows no evidence of this yellow shoulder. Thirdly, hue shifts effected by variations

in the intensity of the spectral stimulants²⁷ (Bezold—Brücke effect), are not considered. Although we think the effects of our scaling the luminance of the spectrum to be of the same order as our color mixtures are small they could, nevertheless, be important. We conclude that the nonlinear inhibition theory is equally as successful in matching spectral naming data as is the linear theory.

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NOTES

¹ G. S. Brindley (1970), and L. M. Hurvich (1981), *Color Vision*. (Sinauer, Sunderland, Mass.)

² For a discussion of the Berlin & Kay work see: S. R. Witkowski and C. H. Brown (1977).

³ For universals see. S. R. Witkowski and C. H. Brown (1978).

⁴ J. S. Werner, personal communication.

⁵ G. Wald, P. K. Brown and P. H. Smith (1955), "Iodopsin", *J. Gen. Physiol.*, 38, 623—681.

⁶ For an early discussion see H. D. Baker and W. A. H. Rushton (1965), "The red-sensitive pigment in normal cones". *J. Physiol.*, 176, 56—72.

⁷ G. Wald (1964) "The receptors of human color vision". *Science* 145, 1007—1016.

⁸ The isolation of different absorbers is discussed in V. C. Smith and J. Pokorny (1975), "Spectral sensitivity of the foveal cone photopigments between 400 and 500 nm", *Vision Res.* 15 161—171.

⁹ This effect is discussed in Jameson & Hurvich (1955).

¹⁰ It is possible to treat the nonlinearity associated with the Bezold—Brücke effect by redefining the coefficients α_i in equation (1) to be intensity dependent. In this way a theory linear in S, M and L is retained.

¹¹ See Brindley (1970), pp. 132ff, 208, and R. M. Boynton and J. W. Onley (1962).

¹² R. M. Boynton, private communication.

¹³ Basic color terms are discussed in Kay & McDaniel (1978).

¹⁴ The linguistic problem is discussed in W. Labov (1973), "The Boundaries of Words and Their Meanings", in *New Ways of Analyzing Variation in English*, (eds R. Shuy and C. Bailey), 340—373, (Georgetown University, Wash. D. C.). On the general theory of categorization see. J. Bruner, J.

Goodnow, G. Austin and R. Brown (1956), *A Study of Thinking*, p. 50ff., p. 247ff. (Wiley, New York).

¹⁵ E. H. Lenneberg (1953).

¹⁶ E. W. Farmer, R. M. Taylor, A. J. Belyavin (1980), "Large color differences and the geometry of Munsell color space", *J. Opt. Soc. Amer.*, 70, 243—245.

¹⁷ We distinguish focal colors specific to a given language from those which represent an average over all languages. The latter we call "generalized" focal colors.

¹⁸ Our focal colors are taken from E. R. Heider (1971), "Focal color areas and the development of color names", *Developmental Psychol.*, 4, 447—455.

¹⁹ Reflectance spectra obtained from Munsell Color, Kollmorgen Corp., Box 950, Newburgh, New York, 12550.

²⁰ Response functions corrected for average lens and macular pigment absorption, converted to energy units and normalized to a peak of 1.0.

²¹ Tints, tones and shades are defined as additive mixtures of maximally saturated hues with white, middle-grey and black, (see F. Birren (1961), *Creative Color*).

²² See: Hering (1964), p. 304—305.

²³ We measured the dispersion width at $3/4$ maximum above zero rather than the usual $1/2$ maximum because we judged the base response level to be unity, (see Fig. 2).

²⁴ Of the 98 Languages Berlin and Kay studied only 20 were available to establish referential focality. Three of these were represented by a single informant. The Vietnamese term *grue* was mistakenly included in the average for focal green, this gives focal green a spurious blue component, (see Kay & McDaniel (1978)).

²⁵ R. T. Kintz, J. A. Parker and R. M. Boynton (1969), "Information transmission in spectral color naming", *Percept. & Psychophys.*, 5, 241—245.

²⁶ C. E. Sternheim and R. M. Boynton (1966), "Uniqueness of perceived hues investigated with a continuous judgmental technique", *J. Exp. Psychol.*, 72, 770—776.

²⁷ R. M. Boynton and J. Gordon (1965), "Bezold—Brucke hue shift measured by color-naming technique", *J. Opt. Soc. Amer.*, 55, 78—86.

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