Where in the World Color Survey is the support for the Hering Primaries as the basis for Color Categorization?*

Kimberly A. Jameson
Institute for Mathematical Behavioral Sciences
University of California, Irvine

KEYWORDS: color perception and cognition, individual differences, color categorization universals.

Corresponding Author:
Kimberly A. Jameson
Institute for Mathematical Behavioral Sciences,
University of California at Irvine
Social Science Plaza, Irvine, CA 92697-5100
telephone: (949) 824-8651 & (949) 650-4022.
email: kjameson@uci.edu
http://aris.ss.uci.edu/∼kjameson/kjameson.html

*Thanks to Angela Brown, Louis Narens, Wayne Wright and Ragnar Steingrimsson for helpful comments. This article extends ideas introduced by Jameson, Bimler, Dedrick & Roberson (2007).

Abstract

Since the 1960's color categorization and naming has been extensively investigated from the point of view of anthropology, linguistics, psychology, philosophy, color perception studies, and computer modeling; and recently the World Color Survey (*WCS*) has provided further support for a view favoring the cross–cultural universality of color categorization (Kay & Regier 2003, Kay 2005, Regier, Kay & Cook 2005). Still, there remains considerable uncertainty regarding which of the various factors thought to contribute to the universality of color categorization can be validated as essential features of color naming phenomena across both individuals and cultures. Moreover, it is unclear whether the empirical and theoretical approaches that are typically used in the area, provide an adequate treatment of the various influences contributing to color naming phenomena. The present article re–examines the widely held view that similar patterns of color categorization across cultures are a consequence of universally shared perceptual experiences across (*a*) individuals within an ethnolinguistic society, and (*b*) individuals from different ethnolinguistic societies. One central working assumption in the literature has been that both intra– and inter–cultural color naming primarily derive their structure from shared *opponent–colors* perceptual experience (*i.e.,* salient Hering colors). Here an analysis of WCS results is presented which does not support the usual shared perceptual experience explanation, and suggests the alternative view that Hering color salience is not supported as different from, or privileged, compared to some non-Hering color saliences. It is argued that while perceptual discrimination unquestionably places substantial constraints on individual color categorization, clearly factors existing outside the individual must also substantially contribute to the intra– and inter–cultural color naming phenomena. A shift in the widely accepted view on this issue is needed to account for such univestigated factors.

1 Introduction

There is considerable debate in the study of human color categorization and naming regarding (1) the degree to which universal tendencies exist in the ways different linguistic societies categorize and name perceptual color experiences, and (2) the possible basis for such universal tendencies. Regarding this controversy the most popular view in the empirical literature is that a pan–human regularity in human visual processing, specifically features related to the *Hering opponent color construct*, gives rise to a standard, pan–human shared phenomenological color experience, and that this in turn is the basis for the empirically demonstrated similarity in color categorization and naming across cultures (see Hardin 2005, Kuehni 2005b, Kay 2005, Kay, Regier & Cook 2005; or Philipona & O'Regan (2006) for an extreme variant of this approach). This view is widely held, and is referred to here as the *standard view* of the area.[1]

Expressions of the standard view can be found throughout the color categorization literature. For example, in recent analyses of the World Color Survey (WCS) data reported by Malkoc, Kay & Webster (2005) state:

> The centroids of the stimuli labeled by basic color terms in these [WCS] languages cluster strongly around similar points in color space, showing that respondents view the spectrum in very similar ways regardless of the varying number of categories into which their lexicons partition it. While counterexamples have been noted [Davidoff 2001] ... the similar clustering across languages suggests that the special and shared status of basic color terms may reflect special and shared properties of the human visual system or of the visual environment (p. 2154, Malkoc, Kay & Webster 2005).

From time to time in the empirical literature, supporters of this standard view mention influences from culturally relative factors on color naming and categorization behaviors (Kay & Kempton 1984, Kuehni 2005a,b).[2] But, in general, explanatory mechanisms beyond those expressed as the standard view have not figured prominently in the mainstream theories of the area.[3]

The present article focuses on one factor widely considered by the standard view to be the basis for color naming phenomena, and explores some plausible, comparatively uninvestigated factors that might underlie color naming phenomena. These are illustrated, in part, through a reexamination of World Color Survey data as it has been presented by Kuehni (2005b).

The aim of this article is to examine the appropriateness of *Hering opponent-color* salience as a theoretical foundation for explaining patterns of color naming in datasets like the WCS, which include many languages that do not use Hering color

[1] Alternative perspectives that emphasize culturally relative influences on color naming phenomena – for example, that supported by D. Roberson, J. Davidoff and colleagues (e.g., Roberson, Davies & Davidoff 2000) – are also frequently seen in the literature, but are not featured in the analyses presented here.

[2] Especially with regard to possible linguistic influences.

[3] A noteworthy exception to this is the recent shift in theoretical emphasis of Regier, Kay and Khetarpal (2007).

terms.[4] The main conclusion reached is that a proper explanation for cross–cultural color naming and categorization should not depend on the Hering opponent colors construct.

The paper proceeds as follows: In Section 2 Hering opponent colors theory is described; Section 3 suggests the extent to which color categorization literature relies on classical Hering color theory; Section 4 examines some evidence regarding whether unique hue experiences are shared across individuals – a key assumption in color naming research; Section 5 re-examines Kuehni's (2005b) analysis of WCS data in light of Sections 2 – 4; Section 6 briefly discusses the circumstances under which the construct of *hue salience* is an appropriate modeling construct in color categorization theory, discusses the appropriateness of alternative modeling constructs to unique hue salience, and provides some empirical support for the suggested alternatives; and Section 7 reviews the main points discussed and offers some conclusions.

2 What are the Hering colors?

The Hering opponent–colors theory (Hering 1920) was a prominent psychological processing component in the original color naming theory of Berlin & Kay (1969), which continues to permeate contemporary theories as an important factor underlying color naming regularity across individuals (*e.g.,* Kay 2005, Regier, Kay & Cook 2005, Griffin 2006, Lindsey & Brown 2006). It was originally proposed by Hering largely as a model of individual color phenomenology, and was subsequently developed as a model of physiological processing by Jameson & Hurvich (1955, 1968).

In its standard form, this three-channel model of color opponency uses salient points in color space, or primaries, based on three opponent axes in color space: Black versus White, Red versus Green, and Yellow versus Blue (as in Figure 1).

This color opponent model assumes that the higher-order structure of individual color appearance, and an individual's color similarity judgments, are directly based on these Hering (black–white, red–green and blue–yellow) color appearance dimensions. In addition, the psychological literature assumes that cognitively the black–white, red–green and blue–yellow axes are largely linear and independent, which is implicit in the widespread use of the unique hue construct (as discussed below) in color categorization research (e.g., Sivik 1997, Hård & Sivik 2001). Thus, as in Figure 1, Hering opponent colors theory classically positions the polar endpoints of a red–green axis, perpendicular to a polar yellow–blue axis, and this conceptualization remains influential in color appearance theory (e.g., Hardin 2000, 2005, Nayatani 2004).

Largely due to the work of Hurvich & Jameson,[5] the Hering opponent–colors model was long considered an appropriate description of both early visual processing (*i.e.,* chromatic response mechanisms in the lateral geniculate nucleus) and higher order (cortical or phenomenological) color representation. This view changed with the empirical findings by Krauskopf, Lennie and colleagues prompted a reanalysis of

[4] Specifically, "blue" and "green" glosses in the WCS languages.

[5] Beginning around the time of Hurvich & Jameson (1957), and including their subsequent opponent-colors articles.

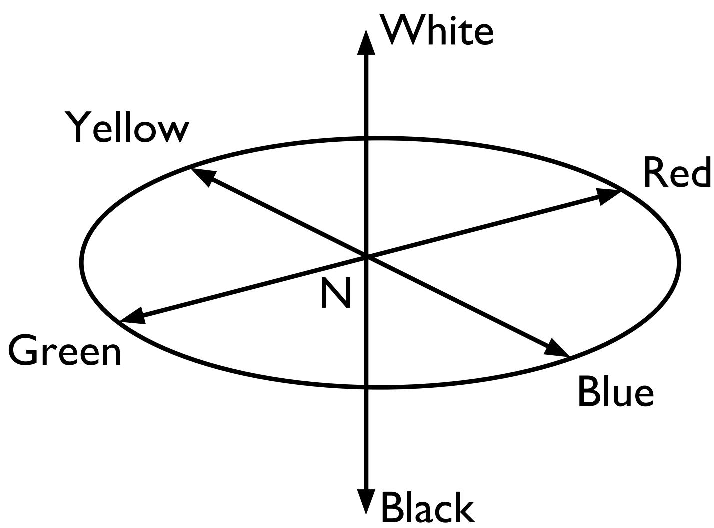

Figure 1: Hering (1920) opponent color axes.

the issue in the 1980's (Krauskopf, Williams & Heeley 1982, Derrington, Krauskopf, & Lennie 1984, Krauskopf, Williams, Mandler & Brown 1986). Since that time opponent color axes, and the relationships between the axes, were known to depend on the level of cortical processing considered. For example, representation at the level of postreceptoral excitation involves color space angles shifted off the classic Hering axes – suggesting a different picture from that shown in Figure 1– such that red is opposed, or nulled, by a blue-green,[6] which is near-orthogonal to an axis formed by a green–yellow nulled by a purple or violet.[7]

Classic opponent colors theory suggests that the axes in Figure 1 should yield unique hue relationships (Hering's *Urfarben*) shown in Figure 2.[8] Instead, when unique hue settings are displayed in an approximately *perceptually uniform* space, it becomes apparent that average Hering unique hue settings (Kuehni 2004) are displaced off the axis endpoints defining the CIELAB space (shown in Figure 3).[9] These

[6]Or the *(L-M)* mechanism – which is somewhat misleadingly referred to as a "red/*green*" mechanism.

[7]Or the "tritan" *S-(L+M)* mechanism (see Gunther & Dobkins' (2003) description of both mechanisms).

[8]Hering's urfarben are six fundamental perceptions, or *pure* color perceptions, which, as defined, when proportionally mixed can produce all color experiences that humans observe. Figure 2 shows Hering's theoretical relationships among four chromatic urfarben, unique yellow (UY), unique red (UR), unique blue (UB) and unique green (UG) on a hue circle plane from a schematic color sphere. According to this theory of phenomenology, UR is nulled (N), or mixed to a neutral appearance, by some proportion of UG.

[9]CIE (Commission Internationale l'Eclairage or the International Commission on Illumination) is the original organization responsible for setting standards for color and color measurement, and developed the CIE XYZ (1931) model which was the first of a series of mathematical models that

unique hue results are discussed again below in detail, in the context of other relevant findings (e.g., Kuehni 2003, 2004).

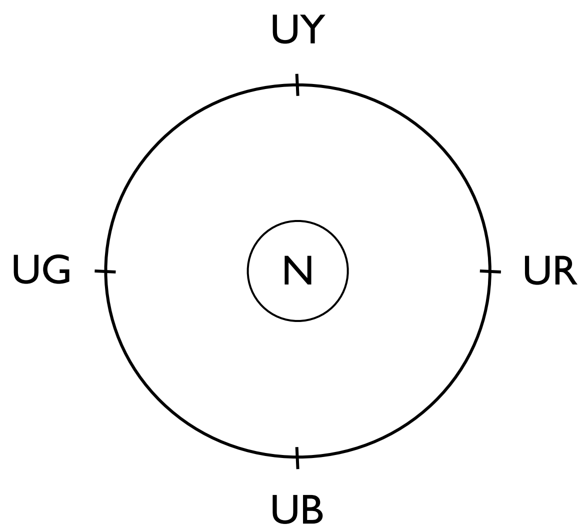

Figure 2: Classical relations among the Hering *unique hues* on the hue circle plane in Figure 1.

3 Hering colors in color categorization research

In an important departure from early philosophical theories of color appearance realism and categorization, Hardin (1988) advanced an empirically motivated view of *subjective color*, making a move towards solidifying the psychological reality of color experience as constructed by an observer. And even for the much loved and historically important Hering colors, Hardin argued for color as subjective and mainly in the heads of perceivers.

Until recently, the color categorization literature resisted the critical examination of the Hering opponent colors (and opponent process physiological theory) as central to the explanation for human color naming phenomena. For example, in a volume edited by Hardin & Maffi (1997), Jameson & D'Andrade argued (*i*) against the physiological reality of classical opponent colors theory (as developed by Hurvich & Jameson (1957)), and (*ii*) against the special status of the Hering colors as plausible explanatory factors for color naming and categorization findings. Jameson & D'Andrade (1997) solidly based their arguments on a clear disconnect between the

describe color in terms of synthetic primaries based on human perception. The primaries are imaginary mathematical constructs that model our eyes response to different wavelengths of light. The CIELAB (1976) system aims to approximate a perceptually uniform color metric, and is often used in color appearance applications and in modeling the structure of psychological color relations. Here it is used for evaluating Hering opponent colors theory predictions because it adequately models color appearance structural relations, and the just-noticable-difference similarity orderings, most likely present in a given individual's phenomenological color space.

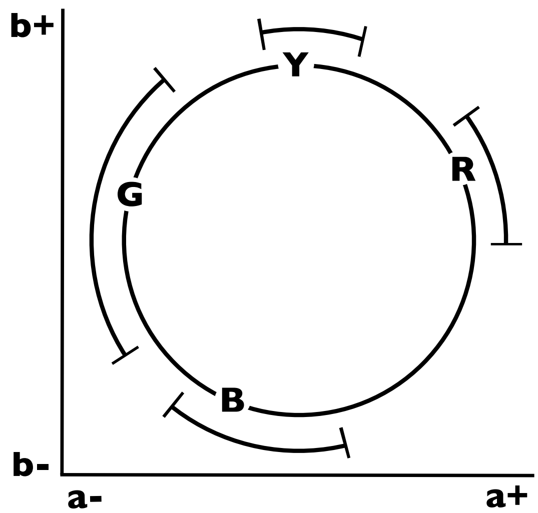

Figure 3: Unique hue settings and ranges in CIELAB (1976) *a* and *b* dimensions. Uppercase letters show the *average* of empirical unique hue setting for red (R), yellow (Y), green (G) and blue (B). Segments adjacent to each setting represent the ranges of unique hue setting averages. Data included were originally discussed by Kuehni (2004), and presented by Bruce MacEvoy at www.handprint.com.

physiological data and the phenomenological data. However, their suggestions were considered extreme and were characterized as dissenting from the mainstream; and contrary to the well accepted theory stating unique hue phenomena were (1) linked to highly specific, early visual processing mechanisms, and (2) responsible for the universal structure of human color categorization and naming.

In current research the Hering primaries construct remains robust and figures prominently in mainstream theory as the basis for universal tendencies in color categorization. For example:

> ... The Kay and Maffi model takes universal constraints on color naming to be based on presumed universals of color appearance for example, on opponent red/green and yellow/blue phenomenal channels ... (Kay 2005, p. 52)

And,

> ... the six Hering primaries: white, black, red, yellow, green, and blue suggesting that these points in color space may constitute a universal foundation for color naming. These foci in color space have also appeared to be cognitively privileged, in non-linguistic tasks with speakers of languages that have dissimilar color naming systems ... (Regier, Kay & Cook 2005, p. 8386).[10]

[10]Regier, Kay & Khetarpal (2007) recently published an alternative to the Hering colors expla-

C. L. Hardin also argues strongly for the psychological reality of individual unique hue appearances (described in Section 2 above):

> ... Given a particular observer in a particular state of adaptation and a particular set of observational conditions, there is a way to ... [empirically assign colors to stimuli]. The names of just four perceptually basic hues — red, yellow, green, and blue — are both necessary and sufficient to describe every hue ... (Hardin 2004, p. 32).

See also Hardin (2005) for a more extensive presentation of this view.

The research cited above underscores the prominent status opponent colors theory continues to receive in color categorization and naming research.

4 Do shared perceptual experiences underlie similar color naming behaviors?

The foregoing discussion raises some questions about the continued use of the Hering opponent colors construct as the explanatory basis for similar patterns of color categorization and naming observed across cultures. To clarify this issue we can examine results on empirically measured Hering primaries in the form of unique hue settings across individual observers, and compare such results with data on best-exemplar choices for Hering colors in Section 5.

Evidence suggests that subjects with normal color vision vary widely in the stimuli they select for the unique hues (*e.g.,* Kuehni 2001, 2003, 2004, 2005a,b; Webster et al. 2000, 2002; Otake & Cicerone 2000; Jordan & Mollon 1995; Boynton & Olson 1990). Figure 3 presented earlier shows CIELAB hue angle ranges of individual unique hue settings across several different studies (Kuehni 2004), illustrating, for example, that the variation for the unique green setting spans a considerable portion on the hue circle[11], compared to unique yellow which shows relatively less variation. Such results exemplify how group unique hue ranges can be rather large as a result of unique hue settings that vary considerably across individuals. (See also discussion in Kuehni 2005a).

Aside from this large individual variation across observers' unique hue locations, there seems to be effectively no correlation ($r = -0.02$) between subject's Rayleigh matches and settings of unique green (Jordan & Mollon 1995, p. 616), as well as a lack of correlation among individual's unique hue settings (both contrary to what

nation using the World Color Survey database (while the present article was *in–press*). Regier et al. (2007) suggests adoption of an Interpoint Distance Model explanation (Jameson & D'Andrade 1997, Jameson 2005a) in their future color naming research.

[11] Jordan & Mollon (1995) observed that although inter-subject variation was substantial, demonstrated by a Gaussian shaped frequency distribution of the unique green settings of 97 observers, with a mean at 511 nm and a standard deviation of 13 nm, the separate estimates of each subject's individual unique green setting showed good agreement (with the average within-subject standard deviation being only 1.63 nm).

classic opponent colors theory might predict). Regarding the latter, Webster, Malkoc, Miyahara & Raker (2000) expressed surprise at observing no correlation among the stimuli individual observers selected for unique hues. That is, participants' unique hue variations did not arise from idiosyncratic individual biases that could shift all of a given individual's unique hue settings to systematically differ from the average settings observed. Thus, Malkoc, Kay & Webster (2005) report:

> ... a subject whose unique yellow is more reddish than average is not more likely to choose a unique blue that is more reddish (or more greenish) than average. The independence of the unique hues is surprising given that many factors that affect visual sensitivity (such as differences in screening pigments or in the relative numbers of different cone types) should influence different hues in similar ways and thus predict strong correlations between them ... (Malkoc, Kay & Webster 2005, p. 2155).

The results of Malkoc et al. (2005) give reason to doubt the shared uniformity of Hering color experiences across individuals, because (*a*) the variation across individuals is substantial and reliable, and (*b*) there is no explanation for (*a*) based on idiosyncratic biases.

Regarding the presumed unique hue basis for color categorization and naming, Malkoc et al. (2005) report:

> ... the range of variation in the hue settings is pronounced, to the extent that the range of focal choices for neighboring color terms often overlap ... [and] ... some subjects chose as their best example of orange a stimulus that other subjects selected as the best example of red, while others selected for orange a stimulus that some individuals chose for yellow ... (p. 2156).

Thus, existing research does not give an affirmative answer to the question posed at the outset of this section (namely, *Do shared perceptual experiences underlie similar color naming behaviors?*), and suggests that a widely shared perceptual experience is not a likely explanation for existing empirical color naming results. To summarize, the reasons for this are: (1) there is a significant lack of evidence for shared unique hue settings across individuals either within or across ethnolinguistic groups,[12] (2) there is not evidence to support the assertion that enough structural similarity exists for even idiosyncratic unique hue settings to explain the amount of observed color naming agreement either within a given ethnolinguistic group, or across ethnolinguistic groups (elaborated in the next section), and (3) there is no clear demonstration that robust,

[12] Asserting that there is an insufficient basis to support that individuals (regardless of whether they are of the same or different cultural affiliation) share similar perceptual experiences when viewing physically identical stimuli, is a claim that follows from the large individual variation seen in measured color matching settings, supported over a wide range of empirical studies, stimulus formats and investigators (see Hardin 2004).

congruent unique hue settings give rise to equivalent internal experiences in any two individuals (as discussed in Jameson, Bimler, Dedrick & Roberson (2006).[13])

From a historical perspective, then, one might also consider that color categorization theory has over generalized Hering's unique hue construct because, unexpectedly, unique hues are not shared phenomenologically, they are not linked to well-defined ranges of *focal chip* reflectances, and (perhaps more importantly) individual idiosyncratic category variation cannot be accounted for by systematic shifts in personal "landmark color" settings,[14] or some identifiable bias across individuals that systematically affects unique hue settings. For these reasons unique hues seem limited as a basis for a primary objective in color categorization research, which is to explain the specific physical stimuli that are individually or collectively identified as color category *focal* exemplars.

Section 5 below examines how these issues relate to cross–cultural color naming data.

5 How does individual variation in perceptual experience relate to cross–cultural color naming results?

Typically, when similarities between two color categorization systems are found empirically, the usual assumption is that it is largely a consequence of similar perceptual experiences across observers. This equally applies to cases of observed similarities across individuals in the same ethnoliguistic society, and cases observed similarities across individuals from different societies, using different color lexicons. Usually such explanations anchor similar perceptual experiences to the Hering primaries. This is a long–standing historical practice that is widely employed and accepted in mainstream research (*e.g.,* Kay 2005, Kay & Regier 2003, Regier, Kay & Cook 2005, Hardin 2000, Hardin 2004, Hardin 2005).

However, given the discussion in Section 4, the question we now need to consider is whether, in general, perceptual experience is the largest component of the explanation behind color categorization similarities, or if, perhaps, other overlooked factors can be identified that play equally important roles in color naming phenomena.

The earlier suggestion that unique hue settings are not shared in a way that identifies specific physical stimuli does not rule out the possibility that other identifiable mechanisms might be responsible for the shared *focal regions* found in some cross–cultural color naming research.[15] For example, cross–cultural focal region similarity

[13]Essentially, there is no way to prove equality of perceptual experiences across the internal states of two individuals due to the fact that they are subjective *Class B* type observations as described by Brindley (1960). Also discussed by Mollon & Jordan (1997).

[14]Or as regularized rotational shifts across individual's categorization results

[15]Throughout this article *focals*, *focal ranges* or *focal regions* are used as defined originally by Berlin & Kay (1969), as empirically identified stimulus regions for category best–exemplars that are

could be the product of *restricted ranges* of observed unique hue settings (*viz.* Figure 3's "Y" setting range compared to that shown for R, B & G), or, alternatively, a non-physically based individual cognitive construct of shared phenomenal color salience for the Hering colors.[16]

To examine the possibility that other mechanisms are at play, and to explore the relationship between Section 4's unique hue variation and color naming patterns, a re–examination of results discussed by Kuehni (2005b) is now presented.

Examining cross–cultural evidence presented by Kuehni (2005b)

Empirical studies that permit a proper assessment of color naming patterns across cultures – especially when done in the field – are costly and demanding undertakings; and much cross–cultural color naming evidence exists showing that subjects with normal color vision vary widely in the stimuli they select as the focal stimuli for basic color terms (*e.g.,* Berlin & Kay 1969, Davidoff 2001, Roberson, Davies & Davidoff 2000, Kay & Regier 2003, Jameson & Alvarado 2003a,b, Lindsey & Brown 2006).

The most recently available database — the *World Color Survey*, or WCS, (Kay & Regier 2003, Cook, Kay & Regier 2005) — is unique and extremely valuable considering the vanishing opportunities to observe color naming behaviors undisturbed by direct contact with outside cultures (MacLaury 2005). The WCS consists of color naming data for 110 unwritten languages from nonindustrialized societies with minimal exposure to external industrialized influences. The WCS field investigations (detailed in Cook, Kay & Regier 2005) were conducted using fewer empirical controls compared to laboratory studies, but because of this they assess more naturalistic naming behaviors than one might encounter under the typical circumstances of a controlled laboratory experiment. The WCS used, in part, a Munsell Book of Color (Munsell 1966; Newhall, Nickerson & Judd 1943) mercator projection stimulus shown here as Figure 4 (with the hue columns reordered as reported by Kuehni 2005b).[17]

Using the publically available WCS database,[18] Kuehni (2005b) examined a universal perceptual categories hypothesis. Esssentially, Kuehni asks: What if across WCS languages, the ranges of stimuli from Figure 4 that are chosen as *focal* exemplars, are found to resemble ranges of empirically observed unique hue settings? If such a correspondence is seen, then, Kuehni suggests, a pan–human universal perceptual basis for color category focals can be argued.

" ... universally shared focal points, or prototypes, in color space ..." (p. 8386, Regier, Kay & Cook 2005).

[16]The construct of shared phenomenal color salience can be described as subjective color experiences that exemplify, for each individual, the best imaginable example of *red*, *green*, *yellow*, and *blue* – irrespective of the actual colors associated with those terms. Nothing would prohibit such highly salient, internal individual color experiences from existing universally, in ways that might provide a basis for color naming similarities across all humans — although verifying such internal events would prove challenging.

[17]Note, that the WCS stimuli has been reproduced here as Figure 4 omits the achromatic stimuli from the center of the Munsell color solid – chips 'A' to 'J' – used in the WCS investigations to represent the ten levels of Munsell value from white through gray to black.

[18]See www.icsi.berkeley.edu/wcs/data.html.

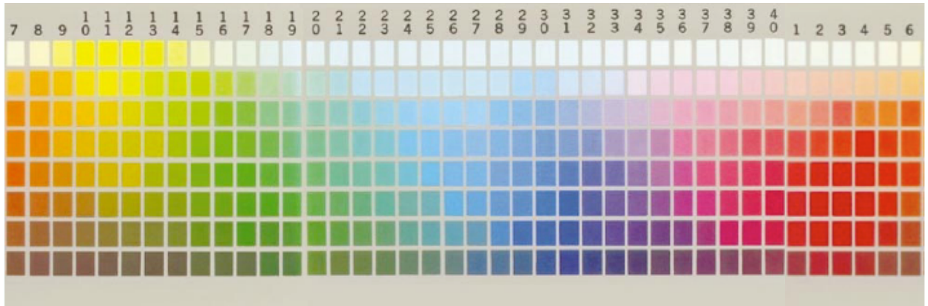

Figure 4: The World Color Survey stimulus reordered to produce a continuous reddish region, with columns 1– 6 appearing after column 40.

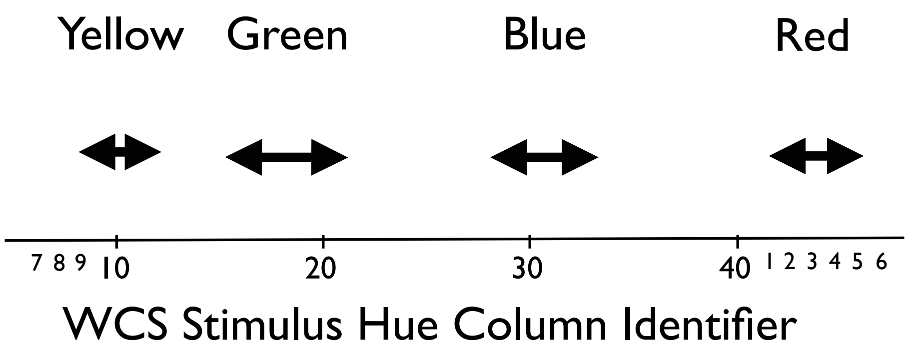

Figure 5: Hypothetical range variation for English focal color terms in the WCS stimulus as might be predicted by unique hue settings (*e.g.,* Figure 3) relative to the WCS stimulus. Depicted ranges are schematic, do not capture brightness variation, and are drawn to illustrate how observed trends in scaled unique hue data might be compared to the WCS stimulus array.

Figure 3 presented unique hue ranges in a CIELAB approximation of perceptual color space, and Figure 5 schematically depicts how such unique hue ranges might be used to predict focal exemplar ranges for English speakers relative to the vertical hue columns of Figure 4's WCS Stimulus. With regard to Figure 4, Kuehni's (2005b) empirical question asks "*do observed unique hue ranges resemble the focal exemplar ranges seen in WCS languages?*" Figure 6's representation, derived from data presented in Kuehni's (2005b) article, permits a renewed examination of this empirical question.

Considering the WCS data

Kuehni (2005b) set out with the aim of examining the above mentioned question for all 110 of the WCS languages. However, as he reports, 65% of WCS languages do not have linguistic glosses for all four unique hue terms (*i.e.,* for *yellow*, *green*, *blue* and *red*). In fact, Kuehni found that only 38 out of 110 WCS languages had the linguistic glosses needed for a comparison against the four unique hue ranges.[19] Also, in some of these 38 languages more than one distinct linguistic gloss was found for unique hue categories. Thus, across 38 languages Kuehni identified 39 distinct glosses for yellow, 39 glosses for green, 44 glosses for blue, and 45 glosses for red categories. Moreover, in the process of identifying the focal term ranges from each language Kuehni also encountered a need to implement focal color choice outlier pruning. That is, in 76% of the 38 languages he considered, some participants "... had distinctly different interpretations of a given color name, as demonstrated with their choice of focal color ..." (p. 412, Kuehni 2005b). Using the same data refinements Kuehni employed, Figure 6 provides an alternative representation of the data found in Kuehni's (2005b) Figure 3.

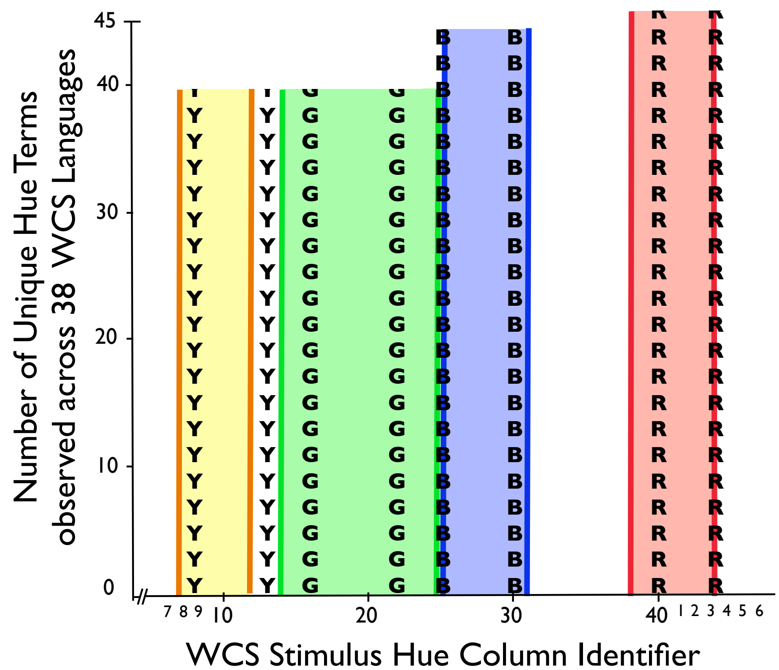

Figure 6: Ranges for unique hue settings and corresponding focal color term ranges in the WCS stimulus array. Two types of data are shown relative to the WCS hue scale on the x–axis: (1) Median focal color term ranges for 38 languages (*i.e.,* columns delimited by congruent alpha–character lines), and (2) Unique Hue ranges (*i.e.,* shaded columns delimited by solid lines). Figure 6's results are adapted from the data presented by Kuehni (2005b), Figure 3 (p. 417).

Figure 6 provides two types of data relative to the WCS hue scale (x–axis): (1) Median focal color term ranges from 38 languages, and (2) Unique hue setting ranges. Figure 6's data differs from that of Kuehni (2005b, Figure 3), by showing the median

[19]Note, of the WCS languages that lacked linguistic glosses for one or more of the Hering primaries, many of these exhibit distinct terms for color categories considered by the standard theory as *noncore*, or *non–elemental*, based on a visual processing emphasis. Observing languages that adopt glosses for theoretically low salience, non–elemental colors, prior to the naming of so–called, highly salient, elemental colors, raises additional concern for the standard view's underlying Hering colors assumptions.

range for each focal term gloss instead of presenting separate ranges for each language examined. Median focal term ranges are denoted by alpha–character columns. Thus, the pair of vertical "Y" lines shows the median denotative range observed for *yellow* focal terms, followed by that for the *green* focal range ("G" lines), the *blue* focal range ("B" lines), and the *red* focal range ("R" lines).

In contrast to Kuehni's presentation of these data, Figure 6 makes use of median focal ranges to emphasize each term's *modal* denotative range, or the central extent of signification across the 38 languages examined. This is both a rigorous and fair alternative presentation of the data as it does not capitalize on the most (or least) variable ranges seen across languages, and instead concentrates on the core meaning of the term given by the modal amount of range variation for each category gloss across the 38 languages considered.[20] This use of modal ranges can be interpreted as the average (or universal) meaning of the four color terms tested across all 38 languages examined.

Thus, the x–axis width of given focal–term column shows the median (across 38 languages) denotative range of that focal term relative to the WCS stimulus array. Y–axis height of alpha–character lines gives the total number of terms observed across the 38 languages for each unique hue category.[21] The second type of data seen in Figure 6 is graphed as shaded columns which show unique hue setting ranges based on the data of some 300 observers.[22] Pairs of solid lines show unique hue setting ranges relative to WCS stimulus array. From left to right, shaded columns show the hue ranges for *unique yellow* settings, *unique green* settings, *unique blue* settings, *unique red* settings.

An important caveat is needed when interpreting the results of Figure 6: Focal color–term ranges are properly interpreted as *best–exemplar ranges* (*i.e.,* " ... universally shared focal points, or prototypes, in color space ..." p. 8386, Regier, Kay & Cook 2005) as opposed to illustrating full category ranges denoted by a given color term.

Now let us consider how Figure 6's alternative representation of the WCS data facilitates the examination of the empirical question: *Do unique hue ranges resemble the focal exemplar ranges seen in WCS languages?*

First, observe that both types of data ranges shown in Figure 4 span such a large extent of the figure's horizontal axis that they essentially imply that only the unassessed "purplish" stimulus region gets excluded from the so–called *highly salient*

[20]Thus, unlike the cases in Kuehni's Figure 3 where a the denotative range of one focal term (say, *yellow*) invaded the territory of an adjacent focal term (say, *green*), for a given language, in Figure 6 these overlapping semantic ranges are limited to a range consistent with a core meaning across the 38 languages. Note, this alternative representation of the data reigns some of the more variable denotative ranges observed (eliminating the need to further prune such cases from the dataset), and, as is seen below, is an alternative representation that does not, in principle at least, pose a hindrance to confirmation of Kuehni's empirical question stated earlier.

[21]Note, y–axis values show that for the 38 languages considered, 39 color term glosses were observed for "yellow;" 39 glosses for "green;" 44 glosses for "blue;" and 45 glosses for "red" appearances.

[22]These unique hue setting data are identical to that shown in Kuehni's Figure 3 — median analyses were not possible because individual data were not available — representing 300 observers that were not part of the WCS sample (see Kuehni 2005b, p. 415).

Hering color regions.[23] Quantitatively, Figure 6's unique hue ranges cover 68% of WCS stimulus hue columns, and the four median focal ranges span 49% of the WCS stimulus hue columns.[24]

With regard to the empirical question posed by Kuehni's (2005b) analysis, it seems that such large variation in both focal and unique hue ranges makes the chance for a failed correspondence between these two types of data ranges exceedingly unlikely. Thus, although Kuehni presents a fairly exacting analysis regarding his universal perceptual categories hypothesis, of these same data he, somewhat surprisingly, concludes "... The results from the 38 languages provide support for the perceptual salience of the Hering UHs." (p. 423, Kuehni 2005b).

Here a different interpretation of these data is offered because although range correspondences do indeed exist, it seems that a criterion of *being anywhere in the color stimulus ballpark* is a poor measure of correspondence in support of a pan-human universal basis for color category focals. In addition, this is not what one would expect if color-naming behaviors were actually based on Hering color appearance universals (Kay 2005, p. 52), and actually does not accord with the spirit of the construct as expressed in the original formulation of Hering's opponent–colors theory (more on this later).

Finally, consider that for 72 of the 110 languages contained in the WCS database, the above comparisons between focal and unique hue ranges is not even possible because those languages do not have glosses for the presumed pan–human salient Hering categories (despite the fact that many have lexicons that include color terms that are robustly used to denote non–Hering colors).

In view of these WCS data, the mainstream's use of the Hering unique hue construct as a pan-human shared phenomenal basis for color category focals and category naming seems much less compelling; and the way that *individual variation in perceptual experience relates to cross–cultural color naming results* seems much less dependent on the Hering unique hue construct.

6 When is the concept of *hue salience*, as suggested by the Unique Hue construct, appropriate for color naming modeling?

Section 5 implies that historically Hering's unique hue construct has perhaps been over extended in its application to color category focal exemplar results. [25] Still,

[23] Purplish stimuli occupy the region between blue and red columns, or the stimuli flanking the hue at column 35.

[24] Compared to median focal ranges observed, focal range extent for the four minimum observed ranges cover 25% of the WCS stimulus, whereas for the four maximum focal ranges observed span 114% of the WCS stimulus (exceeding 100% of the stimulus because some of the observed maximum ranges overlap considerably).

[25] The issue here is not the use of the unique hue construct, *in general*, but its specific use in color categorization theory. There is a long standing practice of connecting unique hue experiences with neurophysiological mechanisms and this has been an important theoretical and modeling emphasis

due in part to the prominence of Hering's opponent colors theory, *color salience* is generally viewed as an important shared color processing feature throughout the color naming literature. Thus, in view of the above mentioned variability of the highly salient unique hues, one might wonder what general role hue salience plays in color categorization and naming. The following analysis of hue salience addresses this issue.

6.1 Revisiting the definition of Hering's unique hues

As classically formulated, in Hering's opponent-colors theory:

> Unique hues are defined as those hues that are phenomenologically pure or unmixed in quality: thus unique green is that green that appears neither bluish nore yellowish. The four unique hues (blue, yellow, red and green) are central to classical Opponent Process Theory and are held to be those colours for which one of the putative opponent processes ... is in balance ... (Jordan & Mollon 1995, p. 614).

Historically, this unique hue construct has presented two important components relevant for color categorization and naming:

(1) Unique hues are theoretically construed as color purity relations (or privileged appearances obtained by color mixture procedures) found in psychophysical experiments, and

(2) They are phenomenologically defined as (i) of high subjective salience, and (ii) are necessary and sufficient descriptors of all visible colors (e.g., Hardin 2004, p. 32),

Figure 7 presents an abstraction of standard psychophysical color mixing procedures used to obtain unique hue settings (shown in Figure 2). Figure 7(a) schematically depicts a process that *narrows in* on an individual's unique yellow (UY) setting by additively mixing proportions of red primary and green primary lights with the aim of canceling any visible red or green tinge in the mixture, and producing a unique, pure, yellow appearance. Thus, determining unique yellow settings requires an individual to successively adjust primary ratios until a yellow appearance that is neither reddish or greenish is achieved. The two-headed arrow in Figure 7(a) depicts this operation of canceling, or the exclusion of, neighboring primaries to achieve a pure unique yellow.

in vision science. For example, while Parry, McKeefry & Murray (2006) show that the red-green and yellow-blue opponent color relations are not the same in the fovea compared to the peripherally presented stimuli, they suggest that some unique hues may serve as anchor points in color space with appearances that stay comparatively stable and do not shift with retinal eccentricity of the stimulus. If proven as an exclusive unique hue characteristic, such a finding would warrant a special processing, and, perhaps, phenomenological salience for some unique hue color appearances, but this kind of finding has not been part of the motivation for using unique hues in color categorization research and theory.

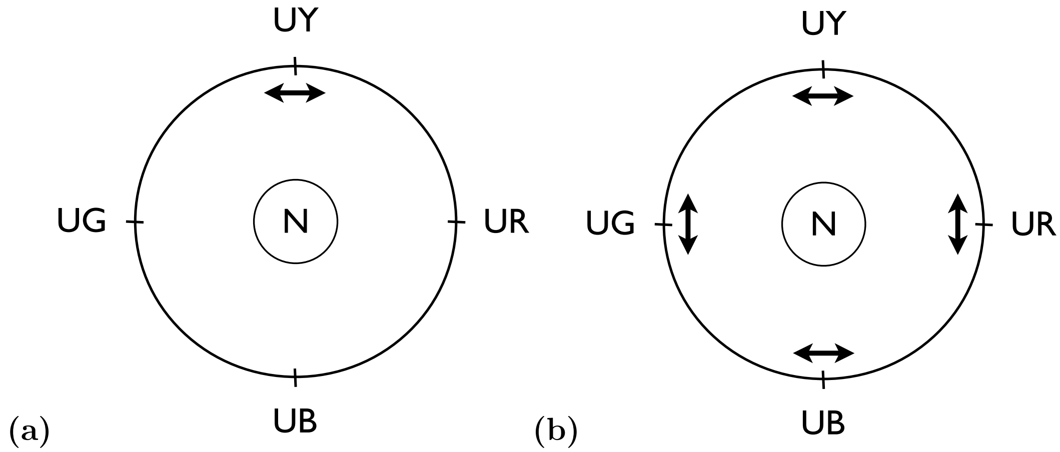

Figure 7: Unique hues defined by a color exclusion operation.

Figure 7(b) shows a similar schematic for all unique hues: UY, UR, UG, and UB. The two-headed arrows placed at these four Hering hue points diverge from the points on the hue circle at each unique hue location to represent the canceling, or exclusion, of the depicted flanking primaries as required by the empirical instructions. The identification of all other Hering primaries via analogous unique hue settings, is a defining feature of the unique hue construct (Jameson & Hurvich 1955).[26]

Is, however, the cancellation procedure just described, with its ability to isolate an individual's psychologically compelling, pure hue settings, necessarily the most appropriate procedure for identifying the set of *privileged perceptual fundamentals* (as the Hering colors are commonly known)?

In point of fact, much evidence supports the existence of other highly salient color space axes comprised of opposing colors that are as empirically robust and compelling as the Hering opponent colors (*e.g.,* Malkoc et al. 2005, Webster et al. 2000, D'Zmura & Knoblauch 1998, Webster & Mollon 1994, Krauskopf, Williams & Heeley 1982, and others). In light of this, what aspect of the empirical procedures used to define the Hering unique hues distinguishes those colors from other opposing hues paired across the color circle? The answer may reduce to a simple modification in the unique hue task instructions.

To illustrate this possibility Figure 8 suggests a slight modification in task instructions that would permit robust *alternative* salient-hue settings. Compared to Figure 7, Figure 8 illustrates alternative salient hue settings possible from the color mixing procedures described above, using a slight modification of instructions for the task. Figure 8(a) depicts (in addition to Figure 7's four unique hue settings) an alternative salient-hue setting 'SO' (denoting *salient orange*) intermediate to the UY and UR positions. The dashed arrowheads converging near Figure 8's 'SO' setting illustrates a *mixing* operation on adjacent primaries (*i.e.,* UY and UR are combined to reach

[26] Where a pure yellow that is neither reddish nor greenish (UY); a pure red that is neither yellowish nor bluish (UR); a pure blue that is neither reddish nor greenish (UB); and a pure green that is neither bluish nor yellowish (UG).

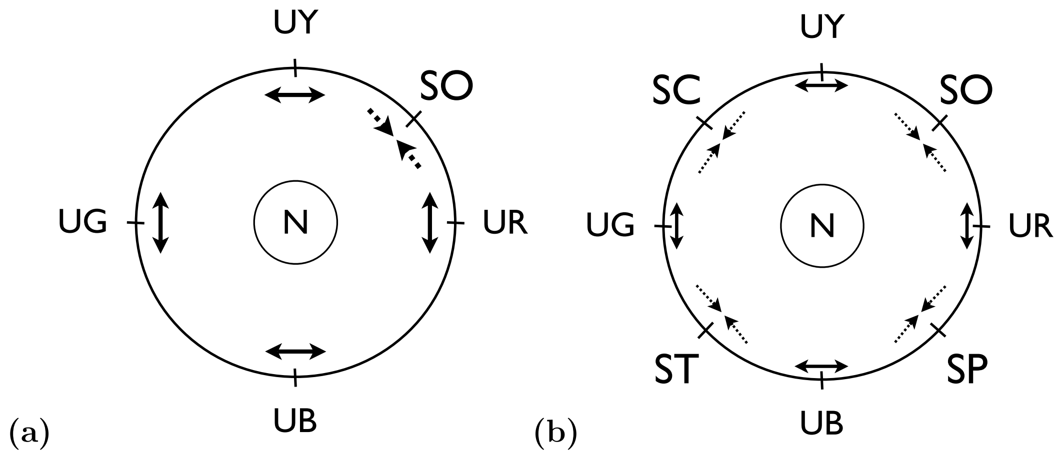

Figure 8: Alternative salient-hues defined by varying color mixing instructions. Panel (a): An alternative salient-hue setting 'SO' (denoting *salient orange*) intermediate to the UY and UR positions. Panel (b): Four proposed alternative salient-hue settings on the hue circle. Hering's classic opponent colors are denoted by 'UY', 'UR', 'UB' and 'UG.' Four new salient hue points are: 'SO' (salient orange), 'SC' (salient chartreuse), 'ST' (salient turquoise) and 'SP' (salient purple). The relationships represented here are not suggested as a physiological processing model underlying any of the colors represented. Figure adapted from Jameson, Bimler, Dedrick & Roberson (2007).

an equilibrium color of subjectively equal proportions of each), and thereby differs from the usual cancellation operation shown in Figure 7. The suggestion is that with a slight change in instruction an individually compelling and robust 'SO' hue setting is equally achievable. That is, for the case of classic Hering unique hue settings the usual kind of instruction of: 'mix two classic primaries *until no classic primary is apparent*' would apply. Whereas for the case of the proposed *alternative* salient-hue settings the instruction would differ slightly: 'mix two classic primaries *until both are equally apparent*').[27] Otherwise, everything else in the "classic" and "alternative" tasks would be the same.

Figure 8(b) illustrates four additional points on the Figure 7(b) circle, denoted: 'SO' (salient orange), 'SC' (salient chartreuse), 'ST' (salient turquoise) and 'SP' (salient purple). The dashed arrows at these four additional points converge at each of the four alternative hue settings to represent four *equally-apparent* mixtures of adjacent classical primaries. These *alternative* salient-hue settings become possible through an uncomplicated, natural variation on the unique hue empirical task, which consists of a slight rewording of the task instructions. Clearly, based alone on the earlier empirical definition of color salience, there seems no good reason not to accept all eight of the subjectively compelling hues shown in Figure 8(b) as all equally compelling privileged perceptual fundamentals.[28]

[27]Neither form of these instructions requires that the "classic primaries" adjusted be the Hering primaries – they could just as well be any other similarly distributed points along the hue circle that were hypothesized to invoke privileged phenomenological salience or processing.

[28]Note that although Figure 8(b) schematically depicts both unique hue points and *alternative* salient-hue point on orthogonal axes and uniformly distributed on the hue circle, the current argu-

The analysis just provided calls into question that idea the unique hues alone connote privileged perceptual salience. It suggests that classic Hering unique hue salience could be tied to empirical task instructions, and that with sensible, minimal, variations to the instructions other alternative hue settings with comparable salience (i.e., empirical robustness, compelling subjective salience, etc.) may be established. This raises some doubt concerning the usual *special status* assumption for unique hues which is implied by part (1) of the two part definition stated at the outset of this section.

Part (2) of the definition given earlier was: Historically, the unique hue construct is *phenomenally defined as (i) of high subjective salience, and (ii) are necessary and sufficient descriptors of all visible colors.* The analysis just described also suggests that all eight hue settings in Figure 8(b) meet the *high subjective salience* requirement.

The *necessary and sufficient descriptor* criterion seems to this author to be (*i*) culturally relative, since languages that do not have glosses for all four unique hue categories (but do have glosses for non–Hering color categories) are apparently able to sufficiently capture all the color experiences of their speakers. And (*ii*) seems to be unrealistic as a criterion in that it does not apply in 65% of WCS languages, or the WCS languages that do not have a full complement of Hering color glosses. In the best of worlds, a *necessary and sufficient descriptor* criterion that is used to argue universal color salience should employ constructs that are similarly manifest across the all groups of individuals assessed. While the Hering color category descriptors may be seen in a subset of the world's languages, they are not found in many languages, and this limits their utility as universally necessary and sufficient descriptors. Finally, in my opinion the *necessary and sufficient descriptor* criterion is really misplaced in the discussion of salient hues identified using perceptual color space considerations, and a better explanation is needed than a linguistically based descriptor rationale if color processing fundamentals are underlying color naming phenomena.[29]

6.2 Empirical support for a more broadly defined notion of hue salience

It seems important to emphasize that recent empirical support exists for Section 6.1's suggestion that the alternative hue points described may be similar in phenomenological salience to the Hering unique hues. Malkoc, Kay & Webster (2005) used hue cancellation and focal naming tasks to compare individual differences in stimuli selected for unique hues (e.g., pure blue or green) and binary hues (e.g., blue-green, or *turquoise* as described above).[30] They did not find any distinction between unique and binary hues in terms of variability in the settings, and, like the unique hues, the binary hue settings were surprisingly uncorrelated with other hues. They

ment does not rely on such color space orthogonality and there is evidence that such regularity is not empirically seen in individual unique hue settings (Kuehni, personal communication, October 2006, and Malkoc et al. 2005).

[29]Although *necessity and sufficiency* may prove to be important factors when cultural considerations are more prominently figured into color categorization investigations.

[30]Malkoc et al (2005) assessed hues comparable to the eight shown here in Figure 8(b).

also state:

> ... the degree of consensus among observers did not clearly distinguish unique from binary hues, nor basic terms from nonbasic terms ... (p. 2165).

Their study shows that there is little to differentiate binary from unique hues, and "... no clear tendency for unique and binary hues to behave differently..." (Malkoc et al 2005, p. 2158). They conclude, "...the processes underlying subjective color experience, and how they are derived from the opponent organization at early postreceptoral stages of the visual system, remain very poorly understood..." (p. 2164),

and that "...the unique hues do not emerge as special and do not alone fully anchor the structure of color appearance for an individual." (p. 2155).

6.3 Summary

Are Hering opponent-color experiences and the unique hue construct the exclusively appropriate perceptual basis for color categorization and naming theory?

The answer to this question could be "yes" if cross-cultural color naming theory aimed primarily to model the classic color mixing results for the subset of languages that have linguistic glosses appropriate for such paradigms.[31] Otherwise, if cross-cultural color naming theory aims to capture commonalities across perceptual color space that are shared/communicated and represented across many additional languages, then a more inclusive and comprehensive theoretical basis is needed to capture all the factors that contribute to the hue saliences that shape color categorization across cultures.

7 Conclusions

The aim of this article was to consider a central assumption inherent in the standard view explanation for color naming behaviors both within and across cultures. I explored the possibility that the empirical results showing individual differences in perceptual processing undermine the argument that a shared phenomenal salience for the Hering unique hues is the sole explanatory factor of shared color category structures within a given society. Other analyses presented suggest that primary mixture settings for Hering's unique hues do not provide a robust basis for explaining the prevalence of WCS color term ranges for the corresponding glosses.

It is important to note that although the present analyses do not find that naming patterns in the WCS data are explained by individual Hering color salience, and it is suggested that a different explanation be sought for the basis of human color naming similarities, it is not implied that no support exists for shared patterns of color naming

[31] Here "classic color mixing" refers to monocular-viewing type experiments used to establish color mixture ratios (which really are not subject to shared communication pragmatics) for Hering primary colors (*e.g.,* determination of yellow settings that are neither reddish nor greenish, and so on), whether employing light mixtures or color papers (see Kuehni, 2004).

in the WCS data (e.g., Lindsey & Brown 2006). In general, the present critique of the Hering colors construct does not bear on uninterpreted statistical demonstrations of shared patterns in the WCS data (e.g., Regier, Kay & Khetarpal 2007).

The view expressed here goes beyond the issue of what relevance the Hering colors might have to color categorization results. In general, color perception, environmental colors and pragmatic constraints must alll place clear structure on color categorization phenonmena. For example, color in the environment frequently signals important information, and primate color perception has almost certainly evolved in ways that allow recognition of such signals (Regan, Julliot, Simmen, Viénot, Charles-Dominique & Mollon 1998; Osorio & Vorobyev 1996). The ability to effectively communicate about valuable color signals, even when individual variation in visual processing exists, seems like a desireable capacity (and many aspects of human evolution underscore the value of within species variation and the value of the evolutionary ability for specialization and adaptation). As does the ability to maintain communication about such information under circumstances where environmental colors vary seasonally and geographically. It therefore seems reasonable to seek explanations for color categorization similarities across human societies that do not strictly depend on fixed visual environments or fixed attributes of perceptual processing. The present article simply expresses the perspective that beyond the typically considered explanatory features, there are clearly pan–human cognitive and communication universals which are arguably more plausible sources for explaining similarities that may be seen in cross–cultural color categorization and naming (see Komarova, Jameson & Narens 2007, Komarova & Jameson in–press, Jameson 2005). If the standard view were to incorporate as a portion of its emphasis the serious investigation of such plausible factors, it seems likely that color naming research efforts might build a more accurate description of the phenomena.

The main conclusion of this article is that although perceptual processing is an important constraint on color categorization and naming, a more extensive set of factors is needed to account for (a) the process by which cultures similarly categorize and name color experience, and (b) the factors that lead such systems to differ across cultures. Explicitly recognizing the limited utility of the Hering color salience argument in color categorization research is an important step towards establishing a proper explanatory model of cross–cultural color naming phenomena. With this in mind, future empirical tests of color categorization hypotheses should take into account perceptual color organization as well as more complicated, pragmatic, social interactions that also play a role in categorization and naming phenomena.

References

Boynton, R. M. and Olson, C. X. (1990). Salience of chromatic basic color terms confirmed by three measures. *Vision Research, 30*, 1311-1317.

Brindley, G. S. (1960). *Physiology of the Retina and Visual Pathway.* London: Arnold.

Cook, R. S., Kay, P. & Regier, T. (2005) The World Color Survey Database: History and Use. In Cohen, Henri and Claire Lefebvre (eds.) *Handbook of Categorisation in the Cognitive Sciences*. Amsterdam and London: Elsevier.

Davidoff, J. (2001). Language and perceptual categorization. *Trends in Cognitive Science, 5*, 382387.

Derrington, A. M., Krauskopf, J. & Lennie, P. (1984). Chromatic Mechanisms in Lateral Geniculate Nucleus of Macaque. *Journal of Physiology, 357*, 241265.

D'Zmura, M. & Knoblauch, K. (1998). Spectral bandwidths for the detection of color. *Vision Research, 38*, 31173128.

Griffin, L. D. (2006). The basic colour categories are optimal for classification. *Journal of the Royal Society: Interface, 3*, 71–85.

Gunther, K. L. & Dobkins, K. R. (2003). Independence of mechanisms tuned along cardinal and non-cardinal axes of color space: evidence from factor analysis. *Vision Research, 43,* 683–696.

Hård, A. & Sivik, L. (2001). A theory of colors in combination – a descriptive model related to the NCS color-order system. *Color Research and Application, 26,* 4–28.

Hardin, C. L. (1988). *Color for Philosophers: Unweaving the Rainbow.* Hackett Publishing Co., Inc.

Hardin, C. L. (2000). Explaining Color Appearance. In Gougen, J. A. and Myin, E. (eds.) Special issue on Art and the Brain, Part II. *Journal of Consciousness Studies, 7, No. 8-9*, pp. 21-27.

Hardin, C. L. (2004). A green thought in a green shade. *The Harvard Review of Philosophy, XII*, 29–39.

Hardin, C. L. (2005). Explaining basic color categories. *Cross-Cultural Research: The Journal of Comparative Social Science, 39*(1), 72-87.

Hering, E. (1920). *Outlines of a theory of the light sense.* Springer. (Translated by L. M. Hurvich & D. Jameson. Harvard University Press, 1964).

Hurvich, L. M. & Jameson, D. (1957). An opponent-process theory of color vision. *Psychological Review, 64*, 384–404.

Jameson, D. & Hurvich, L. M. (1955) Some quantitative aspects of an opponent-colors theory: I. Chromatic responses and spectral saturation. *Journal of the Optical Society of America, 45*, 54–52.

Jameson, D. & Hurvich, L. M. (1968). Opponent-response functions related to measured cone photopigments. *Journal of the Optical Society of America, 58*, 429–430.

Jameson, K. and D'Andrade, R. G. (1997). It's not really Red, Green, Yellow, Blue: An Inquiry into cognitive color space. In *Color Categories in Thought and Language.* C.L. Hardin and L. Maffi (Eds.). Cambridge University Press: England. 295–319.

Jameson, K. A. & N. Alvarado. (2003a). The Relational Correspondence between Category Exemplars and Naming. *Philosophical Psychology, 16(1)*, 26–49.

Jameson, K. A. & N. Alvarado. (2003b). Differences in Color Naming and Color Salience in Vietnamese and English. *COLOR Research & Application, 28(2)*, 113–138.

Jameson, K. A. (2005). Culture and Cognition: What is Universal about the Representation of Color Experience? *The Journal of Cognition & Culture, 5*, (3–4), 293–347.

Jameson, K. A., Bimler, D., Dedrick, D. & Roberson, D. (2006). Considering the Prevalence of the "Stimulus Error" in Color Naming Research. *Journal of Cognition and Culture, 7,* 119–142.

Jordan, G. & Mollon, J. D. (1995). Rayleigh matches and unique green. *Vision Research, 35*, 613–620.

Kay, P. (2005). Color Categories are Not Arbitrary. *Cross Cultural Research, 39*, 39–55.

Kay, P. & Kempton, W. (1984). What is the Sapir-Whorf hypothesis? *American Anthropologist, 86,* 65–79.

Kay, P. & Regier, T. (2003). Resolving the question of color naming universals. *Proceedings of the National Academy of Science, 100*, 90859089.

Komarova, N. L. & Jameson, K. A. (in-press). Population Heterogeneity and Color Stimulus Heterogeneity in Agent–based Color Categorization. *Journal of Theoretical Biology.*

Komarova, N. L., Jameson, K. A. & Narens, L. (2007). Evolutionary Models of Color Categorization based on Discrimination. *Journal of Mathematical Psychology, 51*, 359–382.

Krauskopf, J., Williams, D. R. & Heeley, D. W. (1982). Cardinal directions of color space. *Vision Research, 22*, 1123–1131.

Kuehni, R. G. (2001). Determination of unique hues using Munsell color chips. *COLOR Research & Application, 26*, 61-66.

Kuehni, R. G. (2003). *Color Space and Its Divisions.* Hoboken, N.J.: Wiley.

Kuehni, R. G. (2004). Variability in unique hue selection: A surprising phenomenon. *COLOR Research & Application, 29*, 158-162.

Kuehni, R. G. (2005a). Unique Hue Stimulus Choice: A constraint on Hue Category Formation. Journal of Cognition and Culture, 5(3-4), 387-408.

Kuehni, R. G. (2005b). Focal Color Variability and Unique Hue Stimulus Variability. Journal of Cognition and Culture, 5(3-4), 409-426.

Krauskopf, J., Williams, D. R. & Heeley, D. W. (1982). Cardinal directions of color space. *Vision Research, 22*, 1123–l 131.

Krauskopf, J., Williams, D. R., Mandler, M. B. & Brown, A. M. (1986). Higher order color mechanisms. *Vision Research, 26*, 23–32.

Lindsey, D. T. & Brown, A. M. (2006). Universality of color names. *Proceedings of the National Academy of Sience, 102*, 16608–16613.

MacLaury, R. E. (2005). So-Called Brightness in Color Ethnography: Potentials for LCD Technology in Fieldwork and Categorization Research. *Cross–Cultural Research, 39(2)*, 205–227.

Malkoc, G., Kay, P., Webster, M. A. (2005). Variations in normal color vision. IV. Binary hues and hue scaling. *Journal of the Optical Society of America A, 22*, 2154-2168.

Munsell. (1966). Munsell book of color (Matte-finished). Munsell Color Company. Baltimore.

Mollon, J.D. & Jordan, G. (1997). On the nature of unique hues. In C. Dickinson, I. Murray and D. Carden (Eds), *John Daltons Colour Vision Legacy*, p. 381-392.

Nayatani, Y. (2004). Proposal of an Opponent-Colors System Based on Color– Appearance and Color–Vision Studies. *COLOR Research & Application, 29*, 135–150.

Newhall, S., Nickerson, D. & Judd, D. (1943). Final report of the OSA subcommittee on spacing of the Munsell colors. *Journal of the Optical Society of America, 33*, 385–418.

Osorio, D., & M. Vorobyev. 1996. Colour-vision as an adaptation to frugivory in primates. Proceedings of the Royal Society of London, B, 263, 593599.

Otake, S. & Cicerone, C. M. (2000). L and M cone relative numerosity and red-green opponency from fovea to midperiphery in the human retina. *Journal of the Optical Society of America, A, 17,* 615–627.

Parry, N. R. A., McKeefry, D. J. & Murray, I. J. (2006). Variant and invariant color perception in the near peripheral retina. *Journal of the Optical Society of America, A, 23*, 1586–1597.

Philipona, D. L. & O'Regan, J. K. (2006). Color naming, unique hues, and hue cancellation predicted from singularities in reflection properties. *Visual Neuroscience, 23*, 331-339.

Regan B.C., Julliot C., Simmen B., Viénot F., Charles-Dominique P., Mollon J.D. (1998). Frugivory and colour vision in Alouatta seniculus, a trichromatic platyrrhine monkey. *Vision Research, 38*, 3321–3327.

Regier, T., Kay, P. & Cook, R. S. (2005). Focal colors are universal after all. *Proceedings of the National Academy of Science, 102*, 8386–8391.

Regier, T., Kay, P. & Khetarpal, N. (2007). Color naming reflects optimal partitions of color space. *Proceedings of the National Academy of Science, 104*, 1436–1441.

Roberson, D., Davies, I. R. L., & Davidoff, J. (2000). Color categories are not universal: Replications and new evidence from a stone-age culture. *Journal of Experimental Psychology: General, 129,*369-398.

Roberson, D. & Hanley, J. R. (2007). Color Vision: Color Categories Vary with Language after All. *Current Biology, 17*, R605–R607.

Sivik, L. (1997). Color systems for cognitive research. In C.L. Hardin and L. Maffi (eds.) *Color Categories in Thought and Language*. Cambridge: Cambridge University Press.

Volbrecht, V. J., Nerger, J. L. & Harlow, C. H. (1997). The bimodality of green revisited. *Vision Research, 37*, 407–416.

Webster, M. A., Miyahara, E., Malkoc, G. & Raker, V. E. (2000). Variations in normal color vision. II. Unique hues. *Journal of the Optical Society of America A, 17*, 1545-1555.

Webster, M. A., Webster, S.M., Bharadwaj, S., Verma, R., Jaikurnar, J. Madan, G. & E. Vaithilingham (2002). Variations in normal color vision. III. Unique hues in Indian and United States observers. *Journal of the Optical Society of America A, 19*, 1951-1962.

Webster, M.A. & Mollon, J. D. (1994). The influence of contrast adaptation on color appearance. *Vision Research, 34*,1993–2020.

Webster, M.A. & Mollon, J. D. (1997). Adaptation and the color statistics of natural images. *Vision Research, 34*, 3283–3298.