

SEMANTIC AND PERCEPTUAL REPRESENTATIONS OF COLOR

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Abstract

Perceptual psychology widely operationalizes *color appearance* as a construct with very close, even isomorphic, ties to color naming structure. Indeed, a considerable body of psychological and psychophysics research uses naming-based tasks to derive structural properties of color appearance space. New research investigating the relations linking color similarity and color naming structures suggest that assumptions involving strong structural correspondences between appearance and naming are unfounded. Such research also reveals (i) features of the phenomena for which cognitive and perceptual learning processes play significant roles in establishing individual's color naming similarity structures and (ii) features of the mechanisms underlying stable color naming systems and the ways such shared systems relate to varying individual perceptual color experience. Empirical support for these is summarized, as are suggestions for exploring the largely uninvestigated cognitive processes underlying color appearance and naming similarity relations.

Much research on the cognitive processing of color appearance assumes that for all trichromat observers well-specified perceptual relations exist for predicting how color names will be used to label and partition color appearance space. This assumption is present in theoretical descriptions of shared color lexicons, in the practiced aggregation of color naming data across individuals to derive color naming norms, and in empirical tasks that use lexical labels when assessing individual perceptual salience and individual color space similarity relations. Actually, the perceptual basis for color naming is far from normatively uniform. Simple anomalous trichromats – who in the real world behave as normal trichromats – can have extremely different color equivalence classes compared to normal trichromats, with both smaller and larger metameric discrimination ellipses compared to normal observers (Regan et al. 1994). Even among normal trichromats, observers can experience rather deviant (i.e., ~ 3 s.d.) red-green color weakness (National Research Council 1981), suggesting that discrimination differences among *normals* are enormous (Kaiser & Boynton 1996, p. 343). Large differences among trichromats are also found for “fundamental” unique hue settings, and no uniformity exists in the perceptual distances of unique hue ranges (Kuehni 2001, 2004, 2005). Such results do not support the view that uniform perceptual processing is the basis for color naming and categorization findings (Kay & Regier 2003).

The absence of a uniform perceptual basis for *normal* appearance and naming representation raises some interesting questions. For example, *what is the basis for the cognitive representation of color appearance, and for color categorization and naming systems?*, and *what psychological processes play a role in the representation and maintenance of such systems?* Here it is shown that consideration of the constraints on color representation under normal perceptual variation can provide new insights into the cognitive mechanisms contributing to individual color appearance and naming cognitive representation.

Trichromat Observer Variation

To clarify the *basis of individual color appearance and naming representation*, it seems uncontroversial to suggest that cognitive representation of color appearance similarity must vary in a manner that accords with an individual's variant of color perception. Figure 1 depicts color relations for two

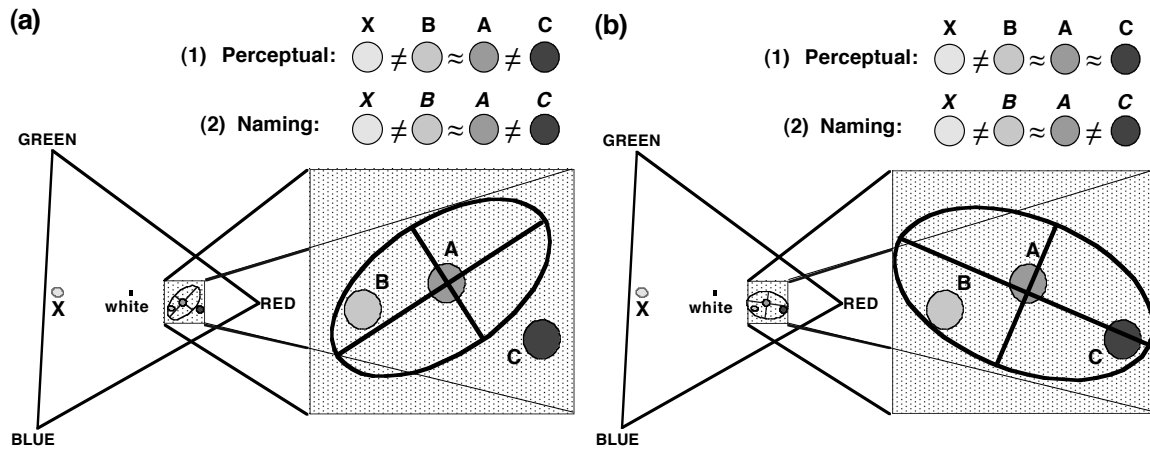


Figure 1. Schematic of a hypothetical *normal* trichromat color equivalence region showing congruent (1) perceptual and (2) naming relations (panel (a) at left). Similarly, panel (b) depicts hypothetical color equivalences for an *anomalous* trichromat. Depicted ellipses are not empirically determined and are not drawn to scale. Analogous differences in trichromat metamerism class ellipses were empirically identified by Regan et al. (1994).

trichromat observers. Both panels (a) and (b) show a triangular slice of uniform *lightness* from a three-dimensional color appearance solid consisting of vertices Red, Green and Blue – analogous to a *CIE* chromaticity diagram. Within the triangular color plane a miniaturized region of color space is shown, and is also enlarged at right. Note in the miniaturized view at left, the stippled area of the space shows three *reddish* color samples (labeled A, B, C in the enlarged stippled view), and a more distant area shows a *bluish-green* sample labeled X. Each Figure 1 panel presents two expressions describing different observer's perceptual and naming relations for A, B, C and X.

Figure 1, panel (a) illustrates that *normal trichromat* perceptual similarity relations can accord with color naming relations. That is, perceptually similar appearances A and B are both distinguished from C, and are named congruently (as relations 1 and 2 suggest). For example, appearances A and B may both be named *crimson* and C named *maroon*. By comparison, Figure 1(b) shows that color appearance similarity relations of an *anomalous trichromat* (a trichromat with one or more shifted retinal photopigments causing systematic differences in the observer's perceptual equivalence classes) can (i) differ from that of the normal trichromat in Figure 1(a), but can also (ii) be named congruent with the “normal” color naming similarity relations in Figure 1(a). Thus, perceptual and naming relations of an anomalous trichromat can be incongruent as shown in panel (b), while those for a “normal” trichromat are congruent. The separate appearance and naming representations illustrated in Figure 1 are suggested as linked by different cognitive *color-naming functions* dependent on observer type (Jameson & Alvarado 2003a).

Figure 1's illustration that color naming can be congruent across observers when color appearance relations are not, implies an idea central to the present theory. Namely, while color appearance similarity can vary, shared color naming similarity relations are normatively stable across a variety of observer types due to socio-cultural and pragmatic constraints present in individual color communications (Jameson 2005). Figure 1 also exemplifies that perceptual variations due to inherited color perception abilities need not impact the sharing of linguistic color relations within an ethnolinguistic group, and suggests that color categorization and naming universals within and across ethnolinguistic groups are not attributable to shared privileged perceptual salience across individuals (Jameson & Alvarado 2003b, Jameson 2005a, 2005b). Instead, individuals share a lexicon's relational structure by communicating with members in their society in ways that reinforce and maintain the stable communication code. The clear purpose of the cognitive *color-naming function* in this scenario is to strive for

maintenance of a shared naming–system equilibrium despite individual variation in perceptual representation or other naming idiosyncracies. Thus, similar to a dichromat, the anomalous trichromat may not perceptually distinguish some colors samples, but she still possesses the *shared naming relations* of normal trichromats (cf., Shepard & Cooper 1992).

The relational mappings of appearance to lexical categories achieved by an individual’s color–naming function is not uniform across color space, or context. Trichromats’ perceptual and linguistic relations can be identical for large color differences, but they need not be identical for smaller color differences. In dichromats, large color differences may be undetectable perceptually but present linguistically. The existence of shared lexical representations, distinct from color perception representations, partially explains why dichromat observers can be undetected in everyday social interactions with trichromats, and suggests a highly cognitive (albeit *automatic*) meta-awareness about one’s own color experience compared to others in the culture. Dichromats understand that Trichromats perceive *red* and *green* as opposing categories, and in everyday interactions they are only at a disadvantage for naming when they have no other cues except color properties to help differentiate two items within their confusion classes.

Retinal Tetrachromat Observers

To clarify *psychological processes that play a role in the development and maintenance of color naming and appearance representations*, it is useful to examine cognitive processing across additional observer types. Recent research has shown that some observers possess the genetic potential for more than the normal numbers of retinal cone classes, and that such observers can experience forms of *weak* or *strong* tetrachromacy (Jordan and Mollon 1993). It is known that color discriminability and dimensionality vary as a function of observer retinal phenotype. The number of just-noticeably-different color perceptions experienced by rod monochromats consists of 10^2 different color experiences (all black and white combinations), dichromat individuals experience 10^3 different color experiences, trichromats approximately 10^6 different color experiences. The obvious question is whether a retinal tetrachromat experiences analogous differences. Retinal tetrachromats occur due to additional variants of photopigment opsin genes acquired by X-chromosome inheritance. When allelic variations for M- and L-cone classes exist at certain positions on the genetic array, shifts in spectral response sensitivity occur that impact color perception. The range and variety of photopigment variants is surprising and implies that, in some populations, retinal processing is almost certainly more varied than originally anticipated by color theory. Although the actual phenotype frequency is uncertain, it is known that a considerable percentage of Caucasian females have the *genetic potential* to express four classes of retinal photopigments (Sharpe *et al.* 1999). Recent empirical studies suggests that retinal tetrachromat genotypes correlate with differences in color categorization, naming and similarity (discussed below), thus presenting further opportunity to analyze the relations between individual color experience and shared color naming representations.

Figure 2 illustrates hypothesized perceptual and linguistic relations for a retinal tetrachromat, depicting, for comparison with Figure 1, a perceptual equivalence–class region potentially available to a retinal tetrachromat. In Figure 2 a small region of *reddish* color appearance is enlarged at right where a hypothetical tetrachromat equivalence–class is centered on sample A and differs from that shown in Figure 1, suggesting shifted or compressed equivalence–class contours compared to a trichromat (generalized from Jameson *et al.* 2001). These hypothetical retinal tetrachromat *perceptual relations* imply that in contrast to Figure 1 observers, a retinal tetrachromat may perceptually distinguish between sample A and B. Despite this perceptual difference, and similar to Figure 1’s anomalous trichromat, the retinal tetrachromat uses a shared color lexicon influenced by the society’s trichromat majority (i.e., expression (2)). This suggests that a retinal tetrachromat may be capable of both encoding greater lexical

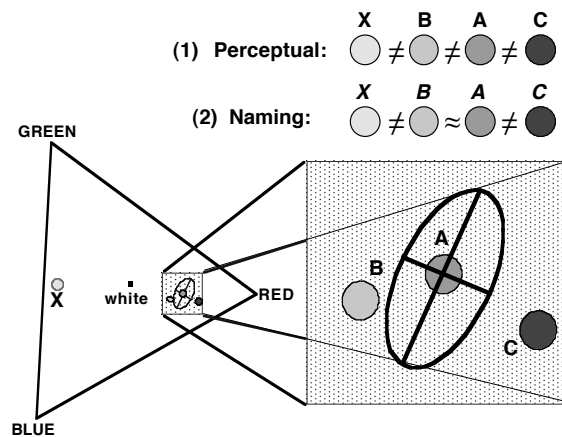


Figure 2. Schematic of a color space region for a hypothetical retinal tetrachromat with differing (1) perceptual and (2) naming relations. Equivalence-class ellipses are drawn strictly for illustrative purposes.

specificity than that found in a normative color lexicon, and greater numbers of categorical distinctions than are agreed upon by trichromats in their society. Of course, the tetrachromat also perceptually resolves more color distinctions than are represented by the lexicon (compared to a Dichromat with *less* perceptual specificity). However, while a society's color lexicon may be adequate as a trichromat color communication code, it may be inadequate, or lack sufficient specificity, for tetrachromat observers.

Earlier it was suggested that social influences and perceptual learning help smooth out color-naming discord potentially arising from perceptual differences among members of a culture. An essential component in this is a tendency for *linguistic charity*, or flexible discourse, among members of a society (Jameson & Alvarado 2003a). For example, as with dichromats, tetrachromat observers may learn to accept and comfortably use a comparatively imprecise mapping of color appearances to color language and categories. A retinal tetrachromat child developing in the company of trichromats may learn color categories primarily by discovering that groups of objects that appear different in color to the child are considered as color-matched by other people. After reliable exposure to these learning experiences such an observer could develop a personal definition of color similarity that says: "Color *matching* denotes when two things have *almost the same* color appearance to me, although other people report seeing them as identical." In this example, the retinal tetrachromat's cognitive construct of a color-match differs from a trichromat's. The net result is that potential disagreements of color labeling among individuals with varying perceptual abilities are minimized. Such a naming function may play a role in other individually varying representations involving color compatibility, color preference, color memory. How tetrachromat perceptual relations might differ from linguistic relations, and how they vary from a trichromat norm, is clarified by recent results on color processing behavior which are now described.

Color Processing Behaviors Correlated with Potential Retinal Tetrachromacy

Psychophysical discrimination paradigms have produced evidence of weak Tetrachromacy (Nagy et al. 1981, Jordan & Mollon 1993), but only one case of reliably strong tetrachromacy (Jordan & Mollon 1993). There are good reasons why some psychophysical viewing circumstances might not register tetrachromat perceptual differences (see Jameson *et al.* 2001). In contrast, empirical assessment under naturalistic viewing circumstances, using a variety of cognitive judgments (color similarity, color categorization, and color naming), show reliable correlations between retinal tetrachromat genotypes and differences in color behavior.

<i>Subject Partition</i>	<i>M</i>	<i>SD</i>	<i>n</i>
(1) Females with retinal tetrachromat genotypes (opsin gene heterozygotes)	10.0	2.96	23
(2) Trichromat Females	7.6	1.80	15
(3) Trichromats (Females and Males)	7.3	1.93	37
(4) Dichromat Males	5.3	1.53	4

Table 1: Means of Individual Median Spectral Delineations for Four Subject Partitions.

Jameson *et al.* (2001) found that females with retinal tetrachromat genotypes experience substantial differences in color perception compared to normal female trichromat controls. They used a task in which subjects delineated categories in a diffracted spectrum subjectively appearing as a luminous “rainbow,” and hypothesized that the ability to perceive and delineate chromatic bands in the spectrum was a function of perceiving noticeable differences in spectral wavelengths. Such differences were expected to covary with the number of retinal photopigment classes possessed. Their results showed significant covariation of tetrachromat genotypes with increased spectral delineation behavior.

Table 1 shows that the spectral bands a subject delineates systematically varies with the number of photopigments a subject is presumed to express (Jameson *et al.* 2001). Classification of subject partition (1) is inferred strictly from the genotype analysis determining heterozygote and is probabilistically linked to the four-photopigment phenotype (with an estimated 56% incidence of genotype occurrence). Partitions (2) to (4) are based on results from both genotype tests and color-vision screening tests. Partition (2) is a sub-partition of group (3). As expected, dichromat individuals delineate fewer chromatic bands than trichromats (Student’s t-test, two-tailed, equal variance $p < .05$). Male Trichromats were not significantly different from female Trichromats ($p = .44$). And a significant difference ($p < .01$) was found between female retinal tetrachromat genotypes (or *heterozygotes*) and trichromats (male and female) subjects. However, the most stringent test rules out possible gender differences in socialization: The number of bands observed between the two female groups (rows 1 and 2 of Table 1) is significantly different ($p < .01$). Overall, Table 1 indicates a systematic relationship between the observed number of bands delineated by subjects and the number of photopigments they are presumed to express. These results suggest that color experience for retinal tetrachromat females is complex compared to “normal” trichromatic color vision; or, less conservatively, that some females show signs of tetrachromacy. (Although whether it is a weak or strong tetrachromacy is unknown.)

Similarly, Jameson, Bimler & Wasserman (2005) found support for a tetrachromat perceptual difference by comparing standardized color vision assessment results between retinal tetrachromat genotypes and three-gene trichromatic genotypes. Novel multidimensional scaling analyses revealed that the Farnsworth–Munsell 100 Hue Test, identifies some retinal tetrachromat individuals (who otherwise exhibit above-average color discrimination) with a non-normative diagnosis, suggesting that such tests do not appropriately capture a tetrachromat’s non-deficient perceptual variation. Figure 3 shows that 32% of genetically identified heterozygotes were diagnosed as false-positive deficient on the F–M 100 test (by Z-values at least 1 s.d. from normal) – all of which had otherwise normal color vision – and among these were heterozygotes who perceived the greatest number of spectral delineations (seen in Figure 3’s top partition). When the F–M 100 test is used as a screen to eliminate subjects with color perception defects (as is the common practice), such misclassifications would result in the omission of some non-defective retinal tetrachromats from the “normal” subject sample tested.

Sayim, Jameson, Alvarado & Szeszel (2005) assess cognitive color behaviors of retinal tetrachromats using triad similarity for color samples and color names across different stimulus sets, and find that some measures differentiate retinal tetrachromat genotypes from trichromatic genotype controls. Analyzing females separately from males, they find that measures of group agreement and consistency

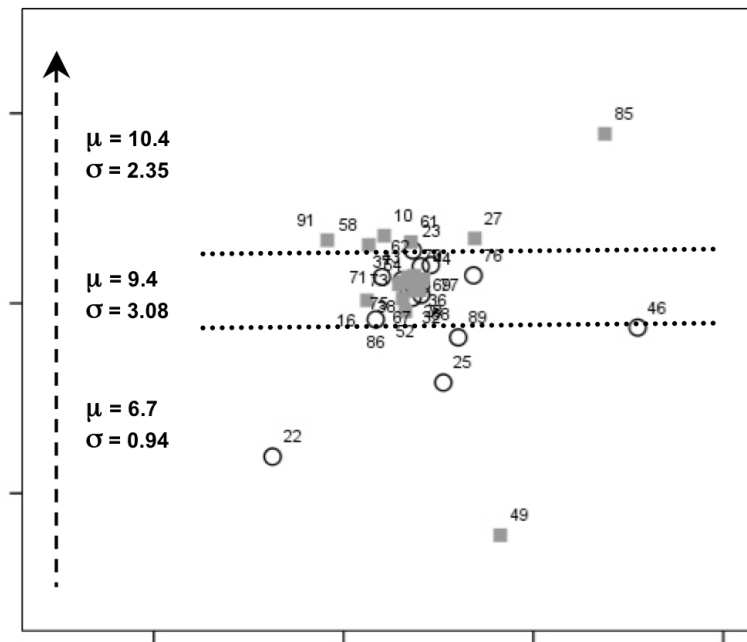


Figure 3. Two-dimensional dissimilarity scaling of F–M100 performance for 37 female subjects. Two horizontal lines were drawn *ad hoc* to emphasize the association between F–M100 performance, genotype, and color perception in the Jameson *et al.* (2001) spectral delineation task. Square gray symbols denote heterozygote females and open circles denote homozygous females. The vertical dashed arrow is a rotated regression line along which banding behavior increases and decreases. Mean and standard deviation banding for partitions are shown.

increase with opsin genotype complexity. L-cone dimorphisms seem instrumental in the behavioral differences because from among all subject groups examined, only the L-opsin gene heterozygotes exceeded criterion on all measures evaluated. Sayim *et al.*'s (2005) results are strong evidence supporting the distinct perceptual and naming representations described above.

Figure 4 summarizes consensus theory (Batchelder & Romney 1988) results for four female genotype groups (Sayim *et al.* 2005). Consensus scores for color triads (left panel) and word triads (right panel) show that between groups significant differences are not seen for the perceptual color triads, although significant differences are found for word triads. Specifically, word triad consensus tends to increase with increases in opsin genotype complexity. Of particular interest is the group with only L-opsin dimorphisms (n=6) which was unique in showing differences in (i) consensus across global and local **color triads** tested, and (ii) good levels of consensus in local **naming triads**, for which all other subjects showed low consensus. A speculative interpretation of (i) is that perceptual variation occurring within the *only L-opsin dimorphism* group is not systematically modeled by the three dimensional color constraints imposed of our CRT-based stimuli. In turn, for this group alone, this could lead to ambiguity in color similarity in the **color triads** tested, producing differences in consensus scores. Although L-cone variation may alter red CRT phosphor sensitivity by 7% (Golz & MacLeod 2003), we have yet to conduct the detailed analyses needed to identify the causes underlying the triad similarity variation we observed. Next, a speculative interpretation of (ii) is that subtle differences in perception arising from expressed dimorphisms might bias such females towards developing color expertise by cognitively heightening color awareness relative to females without such dimorphisms. Over a life-time this subtle increase in color awareness might lead to the cultivation of color naming expertise, possibly producing a more robust lexical code and greater naming consensus as seen in the word triad results for the *only L-opsin dimorphism* group. While both speculative interpretations support the suggestion that observers from the *only L-opsin dimorphism* group may experience something different from “normal” trichomacy, further psychophysical research is needed to determine the nature of the perceptual

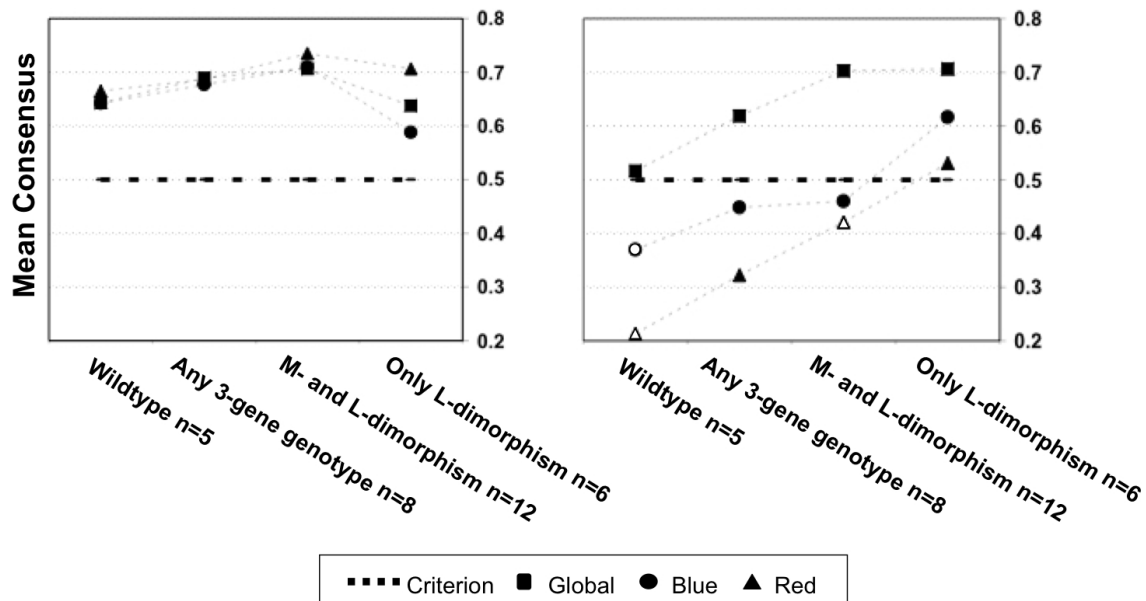


Figure 4. Mean Consensus Scores for Color triads (left panel) and Word triads (right panel) for four Female Genotype Groups. Open symbols denote analyses with low mean consensus and eigenvalues failing to show a single dominant factor. Global results are based on a selected set of color stimuli that span categories (e.g., purple, green, blue, red, etc.), whereas Blue and Red results are “local” results based on separate sets of blue and red color stimuli varying strictly within-category. See Sayim *et al.* 2005 for details.

variation and its influences on color representation. Some have suggested a *dimensional* color difference may exist in retinal tetrachromat observers, this however would require a re-assessment of the widely received assumption of *neural trivariance*, thus it seems prudent to further investigate these phenomena before asserting that dimensional differences are found perceptually.

Summary

Interesting cognitive implications arise by separating color appearance and naming representations. Jameson (2005b) describes these extensively. Clearly, analyses of different observer types are useful for understanding different cognitive influences on color representation. Psychophysical theories of color representation should at a minimum allow for the possibility that some observers experience relational or dimensional differences in color appearance, and still consistently share a normative naming similarity structure. The separate perceptual and semantic representations suggested are linked by a flexible mapping function, or a *cognitive color-naming function* (Jameson & Alvarado 2003a), which should robustly map large color differences to color categories for both normal and anomalous trichromats, but it should be comparatively less robust for mapping small color differences (especially near boundaries). As suggested earlier, different observer types, dichromats, trichromats, anomalous trichromats and possibly functional tetrachromats, could all acquire and use (with varying efficiency) a culturally normative naming system, but they may learn such a system by different manners using different strategies. Jameson and Hurvich (1978) suggested that dichromats learn to use and recognize normative hue terms mappings through correlation with brightness despite the inability to differentiate some hues. By comparison, tetrachromats may implicitly learn that the normative trichromat category tolerance permits a wider range of perceptual variants than would be distinguished in a tetrachromat category structure. It is not necessary to accept the existence of human tetrachromacy to recognize that some of the psychological processing factors described here dictate the separation of individual color appearance and naming representations, or to accept that the cognitive issues separating such representations are greatly under researched in the extensive interdisciplinary color representation literature.

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