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RESEARCH ARTICLE

Unique hues and principal hues

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Abstract
This note examines the different concepts of encoding hue perception based on four unique hues (like NCS) or five principal hues (like Munsell). Various sources of psychophysical and neurophysiological information on hue perception are reviewed in this context and the essential conclusion that is reached suggests there are two types of hue perceptions being quantified. Hue discrimination is best quantified on scales based on five, equally spaced, principal hues while hue appearance is best quantified using a system based on four unique hues as cardinal axes. Much more remains to be learned.

KEYWORDS
appearance, discrimination, hue, Munsell

1 | INTRODUCTION

For over a century, the Munsell Color System has been used to describe color appearance, specify color relations, teach color concepts, and inspire new uses of color. It is unique in the sense that its hue dimension is anchored by five principal hues rather than the more theoretically grounded four unique hues based on the opponent theories of color vision or three primary hues (whether additive or subtractive). The novelty of five principal hues seems to have not limited the application, or success, of the Munsell System. This note examines the difference between specifying hue with four or five principal/fundamental anchor hues and explores the possibility of psychophysical and neurophysiological explanations for the existence of both types of color specification.

In 1975, Judd and Nickerson[1] published an early overview and comparison of the Munsell and NCS systems. They noted the significant difference in hue scaling with Munsell utilizing five principal hues, red, purple, blue, green, and yellow while the Swedish Natural Color System (NCS), based on Hering's opponency, was anchored by the unique, or unitary, hues of red, green, yellow, and blue. In each case, the hues are equally spaced, opposing cardinal axes in NCS and equally spaced in five sectors (as a pentagram) for Munsell. Judd and Nickerson[1] did not offer a firm explanation for the difference in hue scaling, but they did note that the NCS system was designed to specify colors and their relations according to the character of their perception (appearance) while Munsell was set up to create scales of equal color discrimination, or color difference (rather than perception). Perhaps that distinction can be used to explain the difference in number of principal/cardinal hues. In other words, there is a difference between scales on which differences are equally spaced and scales on which appearance is specified unambiguously. This is well known in sensory psychophysics and neurobiology, but is sometimes treated inappropriately in practical colorimetry and color encoding systems.

Valberg[2] reminds that Munsell-type color spaces are representing low-level visual processing, which correlates better with color discrimination or small color differences while NCS-type opponent spaces are representing a higher-level perceptual processing of color appearance, perhaps at a cortical level where judgments about thresholds and small color differences are not made. Valberg,[2] also provided a reasonably detailed explanation of the differences between encoding hue using four versus five anchor hues. Important to keep in mind that either type of specification is encoding the same hues, but simply assigning numbers to those hues, and their increments, using a different rubric. This issue is further explored by examination of opponent cone responses, simple differences between cone types that can be found in the retina and the lateral geniculate nucleus.[2] These responses, such as L-M cone differences, are encoded in the visual system and they are opponent in nature, but their outputs do not directly predict unique hues. Instead, linear combinations of these opponent responses must be used to create a color space where unique hues are the cardinal axes. That leaves open the question of just where in the human visual system unique hues are encoded and/or signaled. Valberg goes on to say about cone difference space:

> The fact that unique hues are not represented by the four axes may be a disappointment to many. Nevertheless, and not surprisingly, response ratios of cells are important. A single hue with increasing chroma corresponds to a straight line, radiating from the white point, representing a constant ratio of the responses of two neighboring cell types. These results are in accordance with psychophysical data, which have demonstrated that non-correspondence between cardinal axes and unique hues is the rule.

Given this rule, perhaps the search for classes of cells that encode unique hues is a futile one since such cells might not be necessary at all. The dimensions that define them are present and that is all that is necessary. It is the possibility of comparisons that is crucial, as Valberg[2] further states:

> Certain abstract chromatic dimensions, such as hue and chroma, may be accounted for at the earliest stages of LGN-inputs to area V1. Here, or later, the firing rates are compared and combined to arrive at the relevant attributes.

Put another way, I can recognize my wife without having a purpose-built "wife detection cell" anywhere in my perceptual system. In addition, of course, individual differences in unique hues should always be recognized and considered.

Given that we do not seem to have direct encoding systems for either opponent-hue systems or five-hue basis scaling systems, it might also be futile to search for the source of the distinction between the two. However, the long-lived success of the Munsell system, commercialized about 100 years ago, and the fundamental perceptual nature of the NCS system, in foundation dating back even further, leads one to question why the large disparity in hue-scale type remains. There is no such disparity in the fundamental nature of scaling the other perceptual dimensions of color (brightness, lightness, colorfulness, saturation, chroma). Is it possible that one hue system is truly better than the other? Or is it the case that both systems are fundamental and useful, but describe slightly different things (like chroma and saturation)? Examining these questions is the purpose of this note. Further details on the origin and design of these color systems and many more, along with great contextual insight, can be found in Kuehni and Schwarz's encyclopedic book.[3]

2 | OPPONENCY AND HUE QUADRATURE

As Hurvich and Jameson elucidated and quantified in the middle of the 20th century,[4] the textbook model of color processing in the human visual system is described in two stages. The first trichromatic stage is represented by absorption of light in the cone photoreceptors, typically labeled L, M, and S for long-, middle-, and short-wavelength sensitive, respectively. These three responses explain wavelength sensitivity and color matching properties (metamerism), but very little about the appearance of colored stimuli. This is the trichromatic visual system originally explained by Maxwell and promoted by Young and Helmholtz. The second stage represent a linear (although not necessarily so) combination of the cone outputs to produce three opponent responses that are typically described as light-dark, red-green, and yellow-blue. This step in the visual processing decorrelates the stimulus signals to help maximize efficiency and comes closer to representing color appearance descriptions. Hering, a contemporary and scientific rival of Helmholtz, promoted opponent-colors theory but he proposed that the opponency happened in the cone photoreceptors themselves rather than as a second stage of processing.[5] It was not until the mid-1900s that the pieces were put together to recognize that both theories were correct, trichromacy at the receptor level and opponency at the ganglion-cell, LGN, and higher levels.

While the modern opponent theory, or stage theory, serves to unify many of the concepts of the Helmholtz trichromatic theory and the Hering opponent theory, it falls short in one important way. While the appearance and nature of the unique hues is fundamental to the opponent theory (although there is no requirement they be on orthogonal axes in any space), unique hues are not encoded directly by the opponent channels found in the early stages of vision. Indeed, as Valberg so clearly pointed out,[2] they are yet to be found directly encoded anywhere in the visual system. Thus, two types of opponent are required to explain visual phenomena, one at a low level that explains color discrimination well and another at a higher level, which might just be ad hoc comparisons of the lower-level signals, to signal our perceptions of the unique hues.

Hering's opponency, at the higher, appearance-based level, is the basis of the Swedish NCS, which was explained in a classic 1981 article by Hard and Sivik.[6] Complete with a diagram of the "good and smiling" sun providing light for the visual stimuli, they explained Hering's opponency and how the NCS system is based on six elementary colors (white, black, red, green, yellow, and blue), which become six "pure" color sensations, and how any color perception can be specified by its resemblance to two, three, or four (with at most two chromatic) of these elementary colors. The limitation to at most two chromatic elementary colors is the expression of Hering opponency in the hue domain. A color can appear to be combinations of red and yellow, red and blue, green and yellow, and green and blue, but no appearance is ever found that is a perceptual combination of red and green or yellow and blue (Hering's opponent dimensions).

In NCS,[6] hue is specified by the visual perception of appearance of one or two (but no more than two) of the unique hues. For example, an orange hue perception midway between unique red and unique yellow would be notated as Y50R to indicate that the perceived proportions are 50% red and 50% yellow. All hue perceptions can be scaled directly in this manner relative to the four unique hues. The NCS atlas represents the hue circle with the four unique hues in the cardinal directions having red opposite green (they never appear together in a single hue perception) and yellow opposite blue (likewise) with the red-green and yellow-blue axes orthogonal to each other. It is worth noting that this geometry is not required by the opponent theory of color vision or the scaling of hue as percentages of two or fewer unique hues, but it is conceptually convenient, or as in the name of the system, "natural."

A similar hue notation has evolved in modern mathematical color appearance models such as CIECAM02. It is called hue quadrature.[7] Once a second-stage mathematical opponent system is set up (similar to LGN responses or CIELAB a*b*), it is possible to specify hue using hue angle from 0° to 360°. Hue angle might provide a reasonable scale for small color differences in hue, but it has no information to directly indicate hue appearance. This is added in color appearance models by defining the hue angles for the unique hues see Figure 1 for an example. In spaces like CIELAB and CIECAM02 the unique hues are often at hue angles of roughly 24° for red, 90° for yellow, 162° for green, and 246° for blue. Note the significantly unequal spacing and the large gap between unique blue and unique red, precisely where Munsell "added" the fifth principal hue, purple. Once the hue angles of the unique hues are defined, NCS-like hue designations can be estimated easily via linear interpolation. For example, as defined for an average observer, an orange hue with a hue angle of 57° (33° away from both unique red and yellow) would have a hue quadrature of 50% R and 50% Y, which is equivalent to the NCS designation of Y50R. Such hue quadrature specifications of perceived hue are extremely accurate, largely regardless of color space as long as the hue angles of the unique hues are accurately defined. Perhaps this should be considered a clue that maybe the spaces themselves are not so critical in the specification of color appearance after all and that the perceptual comparison of whatever sensory dimensions are present is what allows observers to judge appearance (as opposed to defining color discrimination).

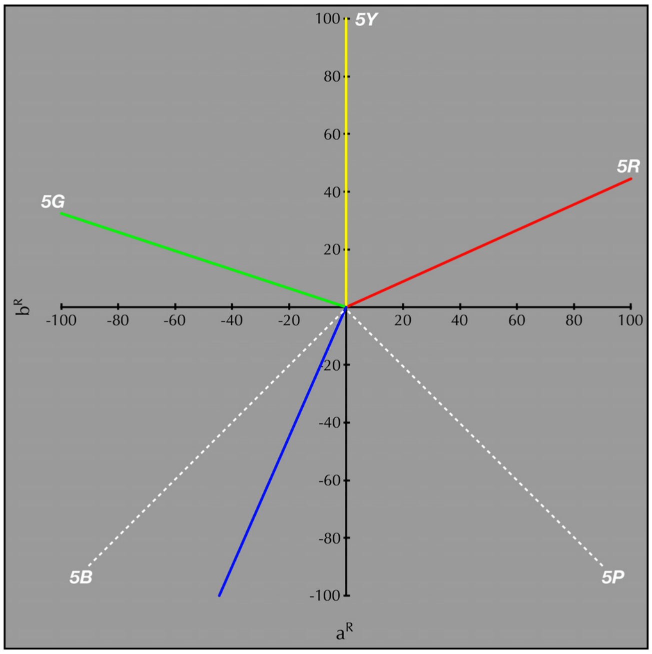

FIGURE 1 A CIELAB-type color space with reddish-greenish (A) and yellowish-bluish (B) dimensions. The hue angles of the unique hues are illustrated with the red, yellow, green, and blue lines. It can be seen easily that the unique hues, with the exception of yellow, do not line up with the color-space cardinal axes. The five Munsell principal hues are also illustrated with labels on the unique hues, where appropriate (5R, 5Y, and 5G) and additional dashed-white lines for the remaining hues (5B, 5P). In this case, it can be seen that the Munsell hues are more evenly spaced around the 360° hues circle in a CIELAB-type opponent space oriented toward prediction of color discrimination. This plot is in the RLAB color space, but the hue angle distribution would be virtually identical in the CIELAB and CIECAM02 JCh color spaces

3 | MUNSELL AND HUE ANGLE

Munsell made the seemingly unusual decision to base the hue dimension in his color order system on five principal hues, red, yellow, green, blue, and purple (RYGBP) rather than the more typical three that would be expected from a system based on color mixing or the four that would be expected from a system based on Hering's opponent theory (which he was aware of). In Munsell's A Color Notation,[8,9] he makes no mention of why five hues were selected but Royal B. Farnum did exclaim in the introduction that "trade names are as nondescript as they are absurd; scientific explanations are unintelligible to the layman; the artist's vocabulary is likewise limited to his profession. Some means of noting colors (is needed for) comprehension and daily use of all mankind."[9] Farnum also stressed the importance of Munsell's system by explaining that an "accurate recording of color is a growing necessity in business where it is rapidly increasing in scope with varied applications." Despite this importance, there remained no clear explanation of the five-hue basis of the Munsell hue scale.

Munsell stated that his system accomplished the goal of having "color anarchy … replaced by systematic color description." Unfortunately, while Munsell clearly defined his system, he was less clear in explaining the sources through which the scales were defined, especially the hue scale. This oversight is a bit mysterious given the technical detail to which the other scales were defined and anchored and the desire for a basis of the system in precise measurement that Munsell so clearly expressed. For example, he was clearly aware of and carefully described much more complicated phenomena such as chromatic adaptation.

> Freshness or fatigue of the nervous system tells powerfully upon color decisions, and even momentary fatigue of the retina may play us unwelcome tricks. It may cause delusions, as in the case of the mother who glanced up from work upon a piece of vivid scarlet cloth, and shrieked at the look on her baby's face, believing its apparent pallor meant death. The rosy complexion of the baby had not changed in the slightest degree, but her fatigued eyes could see no red for the moment, giving only a ghastly mixture of the two remaining sensations, green and blue. Had the cloth reflected a vivid blue-green, she might have been equally overwhelmed by a contrary illusion that the child was feverish.

Munsell's diaries,[10] and their description by Kuehni,[11] provide some insight. On April 5, 1900, Munsell drew a five-pointed star diagram indicating the hues, described the five one-word names of what became the principal hues, five intermediate (two-word names), and 10 more hues using -ish suffixes (eg, greenish-blue). Munsell expressed preference for his "attempted division by five" and for a decimal system (five principal and five intermediate hues for a total of 10). On April 16, he sent a comic referring to five colors to Prof. Rood' who replied that the 5-fold hue idea seemed to be a good one. It is also worth noting that Munsell recorded much earlier that he was aware of Hering's work on opponency from reading Rood's "Modern Chromatics," which references Hering. It is worth noting, however, that Munsell strived to have colors (of equal value and chroma) opposite each other in hue to be additive complements of each other. This additivity also led him to define his five principal hues such that equal segments of the five, in a Maxwell disk device, produced a neutral when spun.

Kuehni[11] shows the star from the diary and mentions the five-hue comic along with Rood's response. He also describes that Munsell tried 3- and 4-color rotating spheres (to produce balanced achromatic colors) but could only achieve balance with equal sectors using five hues. Kuehni also states that Rood suggested "four was the most satisfactory number of divisions of the sphere. However, Munsell was intrigued with the decimal system and looked for reasons to use it."[11] Munsell created the color pentagram with five central colors as single words—red, purple, blue, green, and yellow. Both of Kuehni's books[3,12] on color order system provide no reason for Munsell's selection of five principle hues although ref. 3 provides substantial historical detail on Munsell, NCS and other systems. Thus, the available information seems to point to two reasons Munsell selected five principal hues: (1) his attraction to the decimal system and (2) his desire to have equal segments of the principal hues additively mix to neutral gray (balance).

Figure 1 illustrates the differences between opponent/unique hues and the Munsell principal hues in terms of a CIELAB-like metric color space. The CIELAB space is designed such that equal steps in hue discrimination (small color differences) are also equal increments in hue angle. It can be noted that the Munsell principal hues plot with approximately equal increments around such a hue scale. In other words, the Munsell hues seem to uniformly sample small color differences. However, the cardinal axes (a*-b*) do not represent particularly meaningful hue appearances. The positive b* axis is approximately unique yellow, but the other unique hues fall at non-cardinal hue angles. Thus, to describe appearance in such a space (rather than discrimination) one must first identify the hue angles of the unique hues. It appears there is a dichotomy between the choice of encoding hue discrimination (Munsell, CIELAB) and that of encoding appearance (NCS).

Munsell's fifth principal hue is not required, or helpful, in describing appearance. As Indow concluded,[13] "Of the five Munsell principal hues, Purple was shown not indispensable." This is not really surprising since hue can be described unambiguously using two dimensions (four opposing hues).

4 | CIE COLORIMETRIC MODELS

CIE color difference and color appearance models provide some mathematical mechanisms to specify hue and hue differences.[7] In CIELAB, a color appearance can be approximated using the L*, C^*_{ab}, and h_{ab} dimensions (lightness, chroma, and hue angle, respectively). Hue angle defines hue as a positive angle in degrees measured counter-clockwise from the positive a* axis. This provides an index of hue location in the space, but since the hue angles of the unique hues are not specified by the CIE it has no intuitive relationship with hue appearance or unique hues (see Figure 1). Instead, CIELAB hue angle is a useful measure of hue difference around the entire hue circle, much like Munsell hue. CIELAB measures hue difference but not hue appearance much like CIE XYZ measures metameric color matches (equality or not) without providing a metric of color difference.

Color appearance models, however, include both metrics of hue difference through hue angle (analogous with Munsell) and hue appearance through hue quadrature (analogous to NCS). This is accomplished by defining the hue angles for the four unique hues (see Figure 1) and then using those for anchor points to define hue quadrature, percentage appearance of up to two of the unique hues, using NCS-type designation. As an example, a hue angle of about 58° is roughly midway between unique red and unique yellow and would have a hue quadrature of 50Y, 50R, or NCS designation of Y50R, which clearly indicate the orange hue appearance. Thus, models that include both hue angle and hue quadrature can successfully encode both hue discrimination and appearance (within the uncertainty of visual experiments).

The textbook[7] explanation for this is that hue discrimination (hue angle) and hue appearance (hue quadrature) are encoded in different levels of the visual system and require two different scales. Loosely, the hue-angle/discrimination encoding is likely happening in the retina and LGN while the appearance encoding is happening somewhere in the cortex through perceptual comparisons.[14]

5 | WHAT ABOUT THE BABIES?

Recently, Skelton et al.[15] reported on an experiment that looks at the human parsing of color names into five main hue categories, RYGBP. This descriptive classification of hues is interestingly congruous with the Munsell principal hues and it is worth contemplating the question of whether hue naming and color discrimination have something in common leading to the five main hues. However, the use of color names that line up with Munsell principal hues leads to a "chicken-and-egg" question of whether one produces the other or vice versa (if it even matters as both are reasonable, co-existing, ways to describe hue). Skelton et al. further studied infants using a psychophysical novelty preference procedure and found that their hue categories aligned with those found in the world's color lexicons (and those of the five Munsell principal hues). This suggests that the five-hue categories, along with color discrimination, might be hard-wired at a very young age and before language is acquired. Thus, there is a possible substrate for a fundamental perceptual mechanism and meaning for five principal hues. More work would have to be done to confirm such an hypothesis, but at least there is a possibility.

Similarly, Davidoff[16] discussed that the perceptual categories in hue are yellow, green, blue, purple, and red for the English language. However, the Berinmo people with a simpler lexicon only have red, green, and blue hue names in their language (with perhaps black and purple overlapping). While this might seem to contradict early coding along the lines of five main hues, the lack of a name for a certain hue does not mean that it cannot be perceived.

Therefore, what might be the neural basis for hue discrimination and for unique hues. Hue discrimination seems to be modulated by a system in which the five principal hues of Munsell are uniformly distributed and this seems to correlate well with simple cone opponency in the retina and precortical visual system. The search for neural coding of the unique hues that are so important for color appearance description seems to be a bit more fruitless. In some recent work, Forder et al.[17] suggest that they might have found a signal. They point out that "sustained scientific investigation has not yet provided solid evidence for a neural representation that separates the unique hues from other colors." Then, in their experiments, they identified a signal that can be measured using event-related potentials in the parieto-occipital lobe (a postreceptoral stage) that peaked earlier for unique hues than intermediate hues. This is a marker of a unique hue signal, but it remains to study effects of neural hardwiring, language, and environment. Webster et al.[18] suggest that unique hue perceptions do not need to be directly wired neurally but instead might arise of comparisons of hue angle encodings. These two findings are consistent with one another.

6 | CONCLUSION: IS THE 5TH HUE ACTUALLY FUNDAMENTAL?

The published literature seems to suggest that uniform encoding of hue with five principal hues is just as fundamental as an encoding based on four unique, or unitary, hues. The distinction is that the five-hue encoding with RYGBP equally spaced in hue angle is necessary for the uniform description of hue discrimination while the four-hue encoding with the RGYB unique hues as cardinal axes is required for the direct description of color appearance. Simply put, two different questions (discrimination vs. appearance) are being asked, so two different scales (5-hue vs. 4-hue) are required to answer them.

This is directly analogous to the well-worn argument in perceptual science, dating back to Fechner, of whether thresholds (or JNDs) can be added up to create perceptual appearance scales. The answer to that question, an unequivocal "no," has been known for approximately a century in visual perception research, but is often ignored in other areas.[1,2] Simply put JNDs or thresholds require one type of scale while appearance almost always requires a different scale.

Can it really be that both four-hue and five-hue scales are fundamental to human color vision? Such duality often crops up in science (particles vs. waves?) and there is no problem with that. The simplest resolution is to realize that two different perceptions (discrimination vs. appearance) are being scaled/modeled and then accept that two perceptions are likely to require two different scales. The answer two, which is best can be "both."

Individual differences in color perception are also worth consideration. Webster et al.[18] note significant individual differences in unique hues and a lack of apparent correlation with individual differences in sensor responsivities, or color matching functions. Therefore, something else is introducing both differences and similarities on unique hue assessments. They suggest that since the names of the unique hues are constant, but stimuli responses are not, there is an added confusion and interest in the meaning of the two types of scales. Or maybe, they suggest, hue is encoded "spectrally" and interpreted for different tasks. Emery et al.[14] showed naming and appearance might be encoded by as many as eight spectrally tuned factors at a perceptual level.

Do we need to consider an eight-hue encoding of hue perception? Probably not, but clearly there remains much to learn about hue.

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