Encyclopedia of Color Science and Technology
DOI 10.1007/978-3-642-27851-8_52-5

Psychological Color Space and Color Terms

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Synonyms

Color appearance solid; Color similarity space; Relational color space

Definition

Psychological color space is the relational structure among color stimuli that can be found using empirical tasks that assess color similarities. Color terms are the lexical categories (which can vary across different ethnolinguistic groups) that are used to label, or describe, color appearances organized as meaningful partitions of the psychological color space.

Psychological Color Space

A color-ordering system requires three independent modes of variation to accommodate the full gamut of color experience and arrange all possible hues within a coherent continuum, in which similar pairs of colors are adjacent neighbors. This requirement, so familiar now, only emerged after a long history of trials with one- or two-dimensional schemes [1]. Here colors are considered in isolation as opposed to in the context of other colors where induced simultaneous-contrast effects complicate color appearance.

"Psychological color space" is synonymous with a "color solid" containing all physically attainable hues. Numerous psychological qualities or attributes have been nominated as its underlying dimensions ([1], Chap. 5). The long delay before the acceptance of the three-dimensionality of color space suggests that most of these attributes are not immediately evident and require a trained observer. Perhaps the most intuitive of these qualities, the circular sequence of hues around a color wheel, only became an organizing principle after Newton's description of the prismatic spectrum. Later theorists refined the Newtonian color wheel by inserting nonspectral purples between the red and violet spectral extremes.

One tradition portrays the color solid as a sphere or as a pair of cones or pyramids joined at their bases. The "equator" is the color wheel, containing the purest, most saturated form of each hue. A *hue angle* locates each hue within the rainbow sequence. Perpendicular to the wheel and through its center runs an achromatic axis of gray tones, connecting the polar extremes of white and black. Derived forms of a given hue share the same angular coordinate, occupying space between that point on the wheel and the axis. In effect they comprise one page in a "book of color" radiating out from a central spine. In the Natural Color System – one example of a color space – these intermediate hues are derived from the pure hue by dilution with various amounts of black or white or both.

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DOI 10.1007/978-3-642-27851-8_52-5

Clearly this is a cylindrical coordinate system. As well as the angular coordinate, it implies a radial coordinate (the distance out from the axis), variously labeled as "saturation" or "colorfulness" or "purity." The third coordinate, running parallel to the axis, is some version of "lightness."

Hering [2] argued that in addition to lightness (defined by its extremes black and white), "red" and "green" are the extremes of a second opposition. Each cancels out the other so the two cannot coexist. "Blue" and "yellow" are a third opposition. These three oppositions form an alternative way of spanning color space, with rectilinear axes which specify a hue by its content of "redness vs. greenness" and "blueness vs. yellowness." In terms of radial coordinates, the "cardinal hues" of yellow, red, blue, and green might be located at 0°, 90°, 180°, and 270°, respectively.

In practice the purest yellow hues are relatively light, and conversely the purest purples are relatively dark. Thus, all saturated hues can only be located on the equator of the color solid by treating the lightness scale differently on each of the radial color "pages." The alternative is to treat "lightness" as an *objective* property that can be measured with a photometer and slice color space into planes of equal lightness, with the most saturated example of each hue located empirically in the appropriate plane (in some depictions of color space, lightness is replaced with a "brightness" axis, a more subjective quality which also increases with saturation). The effect is to tilt the color wheel to form an oblique angle with the achromatic axis, distorting the geometry of double-cone and double-pyramid models of color space.

In addition, "maximum saturation" is not a constant quality around the wheel. The most saturated "reds," for instance, are perceptually more intense than the most saturated blues, i.e., more dissimilar from the corresponding gray tone. Incorporating these aspects of color perception produces a less regular color solid. In the widely used "Munsell color space" [3], the radial coordinate (chroma) applies the same metric across hues, reaching its highest values for the intense red hues of intermediate lightness so that they bulge out on the side of the solid. In explanations of how color names are assigned to color space, the geometrical salience of this region marks the red hues as particularly "namable," along with "black" and "white" [4].

Munsell space emphasizes the principle of *uniformity*, that the distance between two hues in the space should reflect the perceptual dissimilarity between them. That is, a given distance at any region of color space, such as a unit increment in saturation level, should correspond to the same inter-hue dissimilarity. This empirical approach also led Munsell to expand the blue/red quadrant of the color wheel and insert "purple" as a fifth cardinal hue, contrary to the Hering polarities.

In another application of the uniformity principle, hue samples were chosen to form a square grid spanning each equal-lightness plane [5]. That is, dissimilarities were intended to be the same between each pair of adjacent samples, as far as departures from Euclidean geometry would permit. The hue samples are also specified by their coordinates on three rectilinear axes L (lightness), g, and y, but the g and y scales were determined afterwards rather than fundamental to this uniform color scale scheme (the OSA-UCS). Again, the resulting color solid is irregular.

An extension of the uniformity principle takes advantage of multidimensional scaling methods (MDS) to explore color ordering. Here ratings of dissimilarity among pairs of hue samples are elicited from observers and analyzed with MDS algorithms, yielding geometrical solutions where points representing the samples are arranged so that distances among them reflect the dissimilarities. In a series of empirical studies, the samples were selected from the Munsell system to vary across all three coordinates [6]. The results generally support that system's uniformity.

Numerous other models of color space exist, emphasizing different aspects of color experience. There is a tension between the uniformity principle and other features that might be desirable, in particular the "linearity" principle that mixtures of two colored lights should be represented by

DOI 10.1007/978-3-642-27851-8_52-5

points along a straight line. CIE tristimulus space is an example of a physiological model where distances are strongly nonuniform.

Why Three Dimensions?

In the final analysis, three dimensions are necessary – though they can be conceptualized and spanned in different ways – because human color vision rests on the existence of three distinct populations of photoreceptor cells in the retina (S, M, and L cones), reducing the spectral information within a given stimulus to three levels of cone outputs. In the first stage of visual processing, neurons in the retina create combinations of the raw cone outputs that are more informative than single values in isolation: a sum (L+M or "luminance") and two cone-output differences (L-M and S-(L+M)). These combinations provide the three axes of *cone excitation space*, widely used in vision research to define experimental stimuli and results.

However, physical light can vary along far more than 3 degrees of freedom. Thus, two stimuli with physically different light spectra may appear perceptually identical ("metamers") and be shown as the same point in color space because they provide the same stimulation to each of the cone classes. That is, trichromatic vision captures only a fraction of the information contained within the spectra of stimuli in the natural visual world. Factor analysis of spectra from a range of objects under a range of lighting conditions indicates that to capture most of the spectral variation would require six or seven distinct photopigments and additional color dimensions [7].

Notably, higher-dimensional spaces are observed in species of reptiles and birds. The three-dimensionality of human color vision suggests that additional photopigments bestowed no advantage over the course of human evolution, i.e., the differences among metamers were not significant in the ecological niches occupied by prehuman primates.

The majority of mammals make do with dichromatic color vision, having only two cone classes. This in turn implies that trichromatic vision *was* adaptive for some primates, with evolution selecting for the divergence of L- and M-photopigment genes. Several adaptive advantages have been advanced to account for this feature of human color space. The difference between M and L cones allows normal trichromats to detect red objects against green backgrounds. In particular, ripe fruit stands out against foliage, as do older, more digestible leaves [8]. Further speculative benefits from the red-green dimension of color space include social signaling, a sexual selection role, and preserving color constancy under changes in lighting conditions [7].

Abnormal Color Space

Color space is convenient for representing the effects of color vision deficiencies (CVDs). Depending on the specific form of deficiency, two colors may be harder to discriminate (i.e., perceptually more similar) when they are separated along a particular direction in the space. This characteristic direction – running between red and green, for the common forms of CVD – is the *confusion axis*. Thresholds for distinguishing between a reference hue and small variations of it are increased in this direction (e.g., slightly redder and slightly greener versions). The locus of hues that are just noticeably different from the reference, which would form a circle when plotted in a suitable color plane, instead becomes an ellipse elongated along the confusion axis.

Alternatively, one could say that the *personal* color space for a CVD observer is compressed, reducing distances along the confusion axis. The degree of compression corresponds to the severity of the deficit. This interpretation underlies the design of widely used panel tests for CVDs. In the extreme case where an entire class of photoreceptor is absent, color space becomes two- rather than three-dimensional, and the color circle collapses to a line. The principle is supported by numerous studies where MDS reconstructed personal color spaces for individuals with CVDs.

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Color Terms

As seen above, color space provides a framework for analyzing color language. For a given *Basic Color Term* (BCT), the range of hues to which that term can be ascribed (its extension) comprises the corresponding *Basic Color Category* (BCC). The BCC can be treated as a geometrical domain by mapping that range into color space.

Each BCC is circumscribed by its boundaries with adjacent color categories. "Red," for instance, has boundaries with the domains of "pink," "orange," "purple," and "black." On one side of the "watershed," a stimulus might be labeled more often than not as "red," whereas a second stimulus, nearby in color space, might attract "pink" as the majority name. Thus, the continuity of color is *partitioned* into color-category domains. There are four points to note here:

1. The vicinity of a category boundary creates *categorical perception* effects in perceptual tasks. These effects are vitiated by verbal interference, indicating that language plays some role in them.
2. For English, the partition is *complete* in the sense that the category domains cover color space in its entirety; there is an applicable term for any realizable color. This is not necessarily the case in every language.
3. Empirically, the domains of English color categories are *connected* and convex. That is, there are no situations where two hues receive the same color term but have some hue between them in color space which is labeled with a different term. In particular, there is no term with a domain separated into two non-contiguous parts.
4. The boundaries of a BCC are part of the BCT's definition, between them circumscribing the hues that it can label. They are not *all* of its definition, however. A color term is also characterized by its *focal hues*, i.e., the hues picked out from the color gamut as prototypal best examples. One may also define the BCC "centroid" hue, the "center of mass" or mean location of its domain in color space (see entry ► *Centroids and Boundary Colors*).

So far the requirements for a color term to be "basic" have not been spelled out. One criterion have been assumed implicitly: a BCT must be understood by almost all speakers of a language, with consensus about its meaning, i.e., few disagreements or misunderstandings resulting from divergent usage. A second criterion is that to be a color term at all, a word must generalize across semantic domains and be applicable to any arbitrary object, as opposed to words like "roan," "palomino," and "dun," specific to animal coats.

In English, 11 color words are BCTs, 3 achromatic terms, and 8 chromatic terms: black, white, grey, red, pink, orange, yellow, brown, green, blue, and purple.

English also provides a rich vocabulary of *subordinate* color terms. Some of these are compounds, generated from a BCT and made more specific by modifying it with a qualifier, e.g., "dark blue" or "bluish green," or with a noun as exemplar, e.g., "sky blue." Others are derived directly from specific objects or pigments (e.g., "lilac" or "magenta"). That is, to use them is to use an implicit metaphor ("lilac colored"). A third criterion for BCTs is that they must not be compounds or still linked to a noun and carrying its connotations. This third criterion requires some care. The BCT "orange" arose from the name of the fruit, but the metaphor has become so routine that it is now a separate word with no citric associations in the minds of speakers.

However, the distinction between basic and subordinate terms is not clear-cut. Rather, "basicness" is a continuous gradient along which can be located by examining their usage, generative properties, etc. [9].

Color terms tend to form a nested, hierarchical pattern, with a broader basic term (*hypernym*) divisible into qualified, more specific *hyponyms*. There are exceptions, color being a continuum

DOI 10.1007/978-3-642-27851-8_52-5

rather than a structure of nested boxes, and a number of subordinate terms straddle the borders between BCTs. "Turquoise" and "teal" lie between "blue" and "green" and are more specific than either, though speakers may argue about their exact usage.

Primary and Secondary Terms

Among the BCTs, a distinction is sometimes drawn between *primary* and *secondary* terms. The former are the six "cardinal hues" comprising the three oppositions of the Hering opponent-hue scheme. Primary terms lend themselves to "unique hue" judgments (see entry ► *Unique Hues*). "Unique green," for instance, is a wavelength that is seen as "green" on its own with no admixture of "blue" or "yellow." Secondary terms are derived from overlaps or intersections of primaries. Three of them – orange, purple, and pink – are the intersections between "red" and its primary neighbors "yellow," "blue," and "white," respectively. "Brown" is the overlap between "yellow" and "black," while "grey" occupies a middle ground between the achromatic extremes of "white" and "black." However, the putative primary/secondary distinction does not appear on the basicness scale as an obvious jump. In addition, it leaves unexplained why some of the terms for primary-term intersections are basic while others (e.g., turquoise) are subordinate.

Primary terms are featured in the *color-naming task*. Here observers characterize a series of briefly presented stimuli using a constrained list of options. A 590-nm light, for instance, might be described as "red with some yellow" (or "70 % red, 30 % yellow"). Repeated exposures build up the precision of the description. The procedure allows subtle nonlinearities in color vision to be quantified, such as the Bezold-Brücke effect (the changes in chromatic content of a colored light as it becomes more intense). In this context, observers are comfortable with describing hues as combinations of "red" and "yellow" when a secondary term such as "orange" is not an available response. This contrasts with the situation when a primary term such as "blue" is absent from the options; observers prefer to leave that component of the stimulus appearance unlabeled ("none of the above").

Color vocabulary becomes more finely divided in the course of language acquisition from childhood to maturity. One might expect primary terms to be learned earlier than secondaries, but the evidence for a standard order of acquisition is equivocal [10]. Cultural factors are involved, with a historical drift toward acquiring terms at an earlier age.

Ontological Status

The ontological status of the BCTs and the categories of experience they represent are still unclear. Are the qualities of "redness" and "blueness" part of the basic genetic patrimony of every human, hardwired into human brains (as the *universalist* position has it)? To what extent is the genetic endowment modified by formative visual environment and cultural factors? (specifically, the color lexicon of one's first language).

A number of MDS studies have elicited judgments of dissimilarities among pairs of color *terms* rather than pairs of hues. The resulting solutions, in which the BCTs are embedded in a *conceptual* color space, show no substantial differences between languages (e.g., English and Mandarin) or from perceptual MDS models [11]. Notably, color-deficient informants internalize the normal relationships within color space such as the diametrical opposition between "red" and "green" [12]. That is, they are intellectually aware of color relationships that they have not detected from observation. MDS has also been applied to *empirical* relationships among BCTs, using the number of samples on the boundary between two BCCs as the index of their similarity.

The issue has inspired comparisons with non-English and non-European languages. It early became evident that many cultures do not emphasize hue as a topic of discussion to the same extent

DOI 10.1007/978-3-642-27851-8_52-5

as English. Many languages do not distinguish "color" from other qualities of surface appearance such as lightness, sheen, or texture: depending on context, words may refer to color or some other visual effect. A notable example is the difficulty of translating putative color adjectives in the *Iliad* from Homeric Greek into consistent English equivalents. In other languages, terms may have chromatic applications but are enmeshed in a web of cultural connotations.

Systematic cross-cultural research requires a standardized palette of hue samples. Informants are presented with each sample in term and asked to identify its color. One such palette, the Munsell array, has been featured in the *World Color Survey* and the *Mesoamerican Color Survey* and in numerous studies of individual cultures (see entry ► World Color Survey).

The methodology is open to critiques, by presupposing for each culture an interest in color as a concept and the presence in each language of color terms per se – neither domain specific nor carrying primarily non-chromatic meanings [13]. That is, it presupposes what it purports to discover, imposing a modern English/European conceptual framework and only capturing those aspects of color discourse that fit. Thus, results from this research tradition may underestimate the prevalence of "non-partition" languages where some colors go unlabeled.

Bearing this caveat in mind, the WCS found the number of BCTs to vary widely across languages, making finer or coarser chromatic distinctions. Thus, many languages subsume "blue" and "green" within a broad "grue" term (some "grue languages" possess a word equivalent to "purple," in further evidence against the primary/secondary distinction). There is, however, a cross-cultural consensus about the focal hues and "centroid hues" of the BCTs. A language may have fewer BCTs than English, but the prototypal examples of their BCCs are generally close to an English equivalent [14]. Moreover, these linguistic distinctions are *prioritized*, in the sense that some are never made unless other "earlier" distinctions have been made already (for instance, if a language marks only three color categories, these will be "dark colors," "light colors," and "red"). These sequence relationships define a "Berlin-Kay sequence" (see entry ► Berlin and Kay Theory).

There is clearly a special status for BCTs. Several explanations for their cross-cultural nature have been advanced [4, 15]. At the same time, CP effects on color-similarity judgments vary between languages, depending on the boundaries between BCCs. These boundaries necessarily shift with the size of the color lexicon but can differ even between languages with the same number of color terms (see entry ► Cultural Relativism and Color Categories).

Cross-References

► Berlin and Kay Theory
► Centroids and Boundary Colors
► Cultural Relativism and Color Categories
► Unique Hues
► World Color Survey

References

1. Kuehni, R.G., Schwarz, A.: Color Ordered: A Survey of Color Systems from Antiquity to the Present. Oxford University Press, New York (2008)
2. Hering, E.: Outlines of a Theory of the Light Sense. Harvard University Press, Cambridge (1957). Translated by L. M. Hurvich & D. Jameson

DOI 10.1007/978-3-642-27851-8_52-5

3. Munsell, A.H.: Atlas of the Munsell Color System, 2nd edn. Wadsworth-Howland, Malden (1915)
4. Regier, T., Kay, P., Khetarpal, N.: Color naming and the shape of color space. Language **85**, 884–892 (2009)
5. MacAdam, D.L.: Uniform color scales. J. Opt. Soc. Am. **64**, 1691–1702 (1974)
6. Indow, T.: Multidimensional studies of Munsell color solid. Psych. Rev. **95**, 456–170 (1988)
7. Maloney, L.T.: Evaluation of linear models of surface spectral reflectance with small numbers of parameters. J. Opt. Soc. Am. A. **3**, 1673–1683 (1986)
8. Sumner, P., Mollon, J.D.: Did primate trichromacy evolve for frugivory or folivory? In: Mollon, J.D., Pokorny, J., Knoblauch, K. (eds.) Normal and Defective Colour Vision, pp. 21–30. Oxford University Press, Oxford (2003)
9. Kerttula, S.: Relative basicness of color terms: modeling and measurement. In: MacLaury, R.E., Paramei, G.V., Dedrick, D. (eds.) Anthropology of Color, pp. 151–169. John Benjamins, Philadelphia (2007)
10. Pitchford, N.J., Mullen, K.T.: The developmental acquisition of basic colour terms. In: Pitchford, N.J., Biggam, C.P. (eds.) Progress in Colour Studies: Volume II. Psychological Aspects, pp. 139–158. John Benjamins, Philadelphia (2006)
11. Moore, C.C., Romney, A.K., Hsia, T.-L.: Cultural, gender, and individual differences in perceptual and semantic structures of basic colors in Chinese and English. J. Cogn. Culture **2**, 1–28 (2002)
12. Shepard, R.N., Cooper, L.A.: Representation of colors in the blind, color-blind, and normally sighted. Psych. Sci. **3**, 97–104 (1992)
13. Saunders, B.: Revisiting basic color terms. J. R. Anthrop. Inst. **6**, 81–99 (2000)
14. Regier T., Kay, P., Cook, R.S.: Universal foci and varying boundaries in linguistic color categories. In: Bara, B.G., Barsalou, L., Bucciarelli, M. (eds.) Proceedings of the 27th Annual Meeting of the Cognitive Science Society pp. 1827–1835. Lawrence Erlbaum Associates, Mahwah, NJ (2005)
15. Bimler, D.: Are color categories innate or internalized? Hypotheses and implications. J. Cogn. Culture **5**, 265–292 (2005)