Color Space and Color Differences

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1. What are color space and color solid?
2. How are they expressed?
3. Scaling of attributes and differences
4. What affects the visual magnitude of stimulus differences?
5. Color difference formulas

The Idea of Color Space and Solid

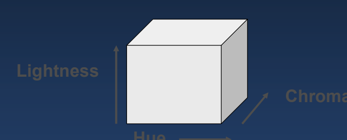
• A million possible object color experiences call for some kind of systematic arrangement.

• Newton and more clearly Helmholtz showed that color experiences have three basic perceptual attributes: hue, lightness and chroma (saturation).

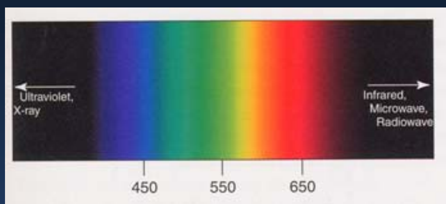
• Hue: red, yellow, green, blue, etc.
Lightness: how light or dark the color appears,
Chroma: how intense the color of a given hue is compared to achromatic (gray) color of equal lightness.

Color Space and Solid 2

• Three attributes suggest geometrical dimensions, resulting in a three-dimensional color space.



• This arrangement is found not to be closely related to our psychological experience.



Hue is arranged according to the spectrum.
Redness at both ends of the spectrum.
Spectrum does not contain purple and some red hues.
When included, a continuous hue circle is formed.

From Hue Circle to Color Space

Anonymous, 1708

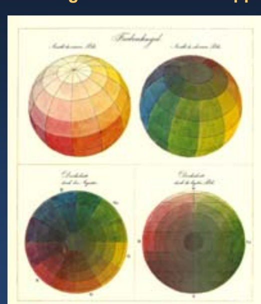
Harris, ca. 1764

In the 18th century the hue circle was expanded to a color plane.

From Hue Circle to Color Space

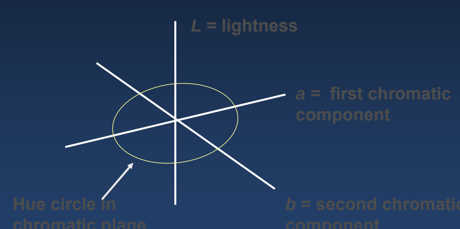
In the second half of the 18th c. 3D-arrangements of colors appeared.

Lambert, 1772

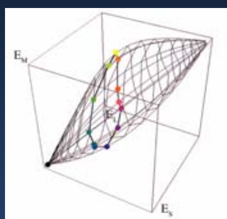


Runge, 1810

Modern color space coordinate system, Cartesian with three axes *L*, *a* and *b*.



Color solid in color space



Optimal object color solid in cone color space

- Color space: 3D axis system.
- All possible color perceptions form a solid in this axis system. Each perception is a point in the solid.
- The form of the solid depends on the meaning of the geometric distances between the points.
- As a result, color solids can be of regular or irregular form.

1. What are color space and color solid?

Summary

- A color space is a three-dimensional coordinate system.
- All human color experiences normally encountered when looking at lights or objects can be placed in a systematic manner. They form color solids in the space.
- Different kinds of color spaces and solids have been developed, differing in the meaning of geometric distances in the space.

2 How are color spaces and solids expressed?

A. Colorant or light mixture spaces

B. Psychophysical spaces

C. Empirical perceptual spaces (differences)

- Hering type
- uniform or isotropic space

D. Psychophysical models of perceptual spaces

A. Colorant or light mixture spaces

Colorant mixture spaces are based on three primary colorants, often yellow, red, and blue, and the results of their systematic mixture.

This cubic space is either the mixture space of the printing primaries yellow, cyan, and magenta, or a light mixture space, e.g., a Color Picker space in Adobe Photoshop. Here, the solid fills the entire space.

2. How is color space expressed?

B. Psychophysical spaces

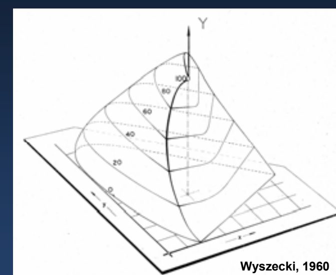
• Based on reflectance data of materials, SPDs of lights, and average human cone sensitivity or color matching functions.
• Represent activity of cones interacting with the light entering the eyes. They do not represent brain processes; are not in close agreement with what we experience.

L, M, S cone space, CIE *X, Y, Z* tristimulus space or *x, y, Y* space all contain the same basic information and are linearly related spaces (no compression).

2. How is color space expressed?

Surface of optimal object color stimulus solid in the CIE *x, y, Y* space

Basis plane of solid: CIE chromaticity diagram. The example shows the object color limits as viewed in standard daylight. Its surface is known as the MacAdam limits.



Linear psychophysical spaces are not perceptually uniform.

2. How is color space expressed?

C. Empirical perceptual spaces

Based on perceptual scaling; perceived differences.

1. Scaling according to unique hue content, blackness and whiteness (Hering method).

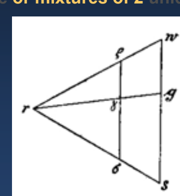
2. Scaling according to attributes hue, chroma, lightness (example: Munsell system).

3. Division into steps of equal perceived difference in different directions (attempts at a uniform space).
A uniform or isotropic space and solid contains the most information (example: OSA-UCS).

2. How is color space expressed?

Hering Solid

In mid 19th century German physiologist Ewald Hering proposed attributes: hue, blackness, and whiteness. Hues are either unique or mixtures of 2 unique hues.

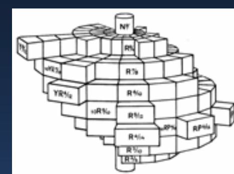


Hering attributes result in a regular, but not a uniform double cone space.

Hering Solid 2

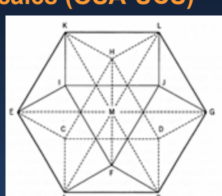
A modern implementation of a Hering space is the Swedish Natural Color System (NCS).

The Munsell system



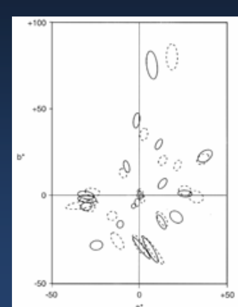
- The Munsell system is roughly perceptually uniform and based on attributes hue, chroma, and value.
- No simple geometrical solid: different hues have different maximum chroma at a given lightness.
- Attribute divisions are approx. uniform within but not among themselves.

Optical Society of America Uniform Color Scales (OSA-UCS)



Internal structure based on the cubo-octahedron, 12 nearest neighbors, space is filled without gaps.
Uniformity in 6 directions only and hue superimportance make OSA-UCS not isotropic, but it is more uniform than the Munsell solid.

Hue Superimportance



- The human color vision system detects reflectance differences that result in hue differences more easily than if they result in chroma or lightness differences.
- Unit chromatic differences form ellipses in a Euclidean chromatic diagram (ellipsoids in color space) pointing toward the origin.
- Euclidean color spaces cannot be isotropic or uniform. Applies to psycho-physical as well as perceptual color spaces

D. Psychophysical formulas fitted to global perceptual data

- Relates physical measurement
- No attempts to fit a psychophysical formula to NCS system. It would be very complex.
- Several attempts to fit a formula to Munsell system data. A rough approximation is the (non-linear) CIELAB formula.
- A formula was fitted to the OSA-UCS experimental perceptual data. OSA-UCS and Munsell systems differ considerably. OSA-UCS more uniform.

2. How is Color Space Expressed?

Summary

In terms of attributes and their divisions, or complex color differences.

Important basic psychological attributes of object colors are: hue, chroma and lightness.

Four basic kinds of color spaces.
An important kind is the isotropic (uniform) space: perceptual differences in all directions have same magnitude. Not fully possible.

Other kinds of color spaces are regular but not uniform.

3

Scaling of attributes and differences

Perceptual attribute measurement

- Attribute measurement is described as:
  "The process of assigning numbers or other symbols to the things in such a way that the relationship of the numbers or symbols reflect relationships of the attribute being measured. A particular way of assigning numbers or symbols to measure something is called a scale of measurement."
  Sarle, 1995
- Hierarchy of scales with increasing mathematical meaning: nominal, ordinal, interval and ratio. Of particular interest: interval scales.

Scale Hierarchy

- Ordinal scales: sorting a series of percepts by magnitude without regard to magnitude of difference.

- Interval scales: estimating the size of intervals between percepts; not concerned with absolute size of the percepts. Used in color difference evaluation.

- Ratio scales: scales that have a natural origin (e.g. Kelvin temperature scale) and in which all intervals are perceptually equal.

Perceptual Determination of Color Differences

Complex color differences can be judged
- separately according to three attributes hue, lightness and chroma (one-dimensional)
- as total color differences (three- or multidimensional).

They can be judged
- at the threshold level (just noticeable difference)
- at the level of small differences (of interest in color quality control)
- as relatively large differences (such as in the Munsell system or larger).

Results of judging small and large differences do not mesh.

Measurement vs. Judgment

- Are color difference assessments neutral measurements or judgments subconsciously or consciously influenced by past experiences or current strategies of observer?

- Extensive experience shows psychological scales are always influenced by our past experiences or current strategies.
They are the result of judgments.

Do humans have a tool in the brain to accurately determine color difference intervals?

- Answer not known but unlikely to be yes.

- Would require apparatus in the brain comparing two fields of different color and ‘measuring’ their difference.

- Early ancestors had no need to assess magnitude of color differences. Knowing there is a difference was much more important than knowing the size of the difference.

- Individuals differ considerably in their assessment of color differences.

Scaling of small supra-threshold differences (quality control)

Such differences usually multidimensional: in all three attributes simultaneously.

Assessed by one of several methods:

1. Absolute judgment
   a. acceptability: is the color acceptable as a commercial match?
   b. pair comparison: is the difference between samples A and B smaller or larger than between B and C?

continued

2. Comparison against reference pair
   a. is the difference between samples A and B smaller or larger than between reference samples M and N? M and N are usually gray and represent a lightness difference.
   b. if the difference between reference samples M and N has a value of 1 what value would you give to the difference between samples A and B?

3. Comparison against gray scale
   which gray scale step is comparable in size to the step between samples A and B?

Averaging perceptual data

- Perceptual results from observers vary considerably.
- Average results are calculated from results of several observers.
- Averages from different experiments differ considerably.
- The reasons for the differences in results for different experiments are not yet known.
- Color difference formulas are based on averages from different experiments (averages of averages).

3. Difference Scaling
Summary

Three basic attributes of color experience can result in a roughly uniform color space: H, C and L. Other kinds of attributes result in regular, but not uniform color spaces.

Psychological attribute scaling can be done with scales with different explanatory power: nominal, ordinal, interval or ratio.

Color differences can be scaled at different sizes of unit difference: threshold, small, large, one-dimensionally or multidimensionally, by different methods.

Results from multiple observers and multiple experiments are averaged.

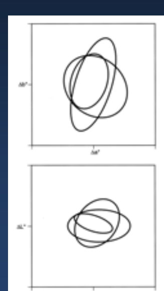
4

What affects the visual magnitude of stimulus differences?

Individual differences in assessing color differences

Color-normal individuals assess color differences with much inter-observer variability.

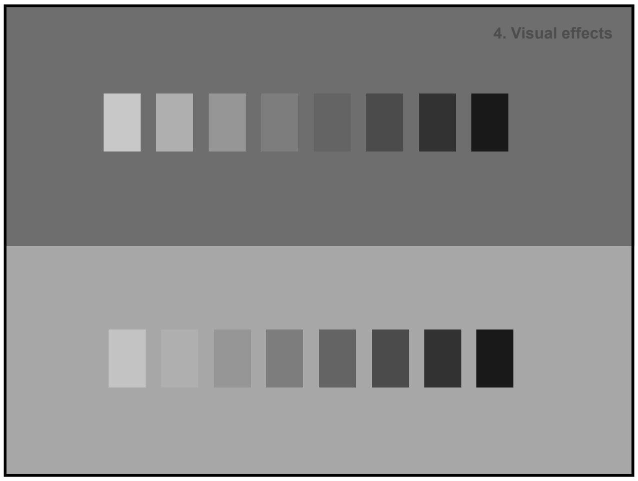
Two views of unit difference ellipsoids fitted to results from individual observers.
RIT-DuPont data set.



Crispening Effects

- The smallest stimulus increment to see a difference of a given magnitude is required if the chromaticities and the lightnesses of the test fields straddle those of the surround: the crispening effect; applies to chroma and lightness.

- Choice of surround is critical in determining the color samples representing a uniform color solid.



4. Visual effects

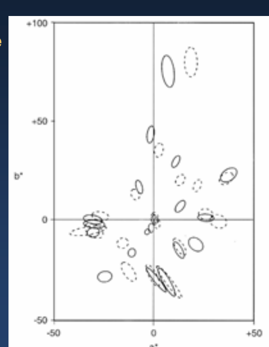
There is not just a crispening effect but also a proximity effect (simultaneous contrast).

In addition there is a texture effect important in case of textile samples.

4. Visual effects

Hue superimportance effect

- The human visual system is twice as sensitive to hue differences than to chroma and lightness differences: hue superimportance effect.
- Unit difference contours in a Euclidean diagram are always ellipses and in a space always ellipsoids.
- Requires special mathematical treatment.



4. What Affects the Visual Magnitude of Stimulus Differences? Summary

Individuals perceive visual color stimuli differently.

Different surrounds and resulting crispening effects affect the size of perceived difference.

Proximity between test fields as well as test field structure influence perceived difference.

Hue superimportance effect affects relationship between measured and perceived results.

5

Color Difference Formulas

Color Difference Formulas

An accurate mathematical model of a uniform space must either

1. closely represent the mechanisms of our color vision system or

2. have sufficient variables to model the relationship between perceptual and physical data (reflectances) accurately. Recall that the space is not Euclidean!

Today we do not have sufficient information about our color vision system to develop a model of the first kind.

CIE efforts: from U*V*W* to CIEDE2000

• Since the 1960's the CIE has proposed several color space/difference formulas:

1964: U*V*W*
1976: L*a*b* (CIELAB) and L*u*v* (CIELUV)
1994: CIE94
2001: CIEDE2000

The 1964 and 1976 formulas represent color spaces. The last two formulas are color difference formulas modifying CIELAB to achieve improved correlation against visual data.

The CIELAB Color Space Formula 1

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16$$

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{1/3} - \left(\frac{Y}{Y_n}\right)^{1/3}\right]$$

$$b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{1/3} - \left(\frac{Z}{Z_n}\right)^{1/3}\right]$$

Euclidean space with lightness scale L^* and chromatic scales a^* and b^* in form of Cartesian coordinates; based on some simplifications:

• L^* scale represents Munsell value scale
• cube root assumed to apply equally

The CIELAB Color Space Formula 2

- The color difference formula in the standard Cartesian form is

$$\Delta E = [(\Delta a^*)^2 + (\Delta b^*)^2 + (\Delta L^*)^2]^{0.5}$$

- *a** approximately represents greenness-redness, *b** approximately blueness-yellowness, *L** lightness.

- In the polar coordinate version it is possible to calculate approximate correlates for hue and chroma differences:

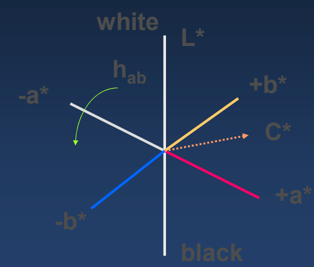
$$\Delta E = [(\Delta C^*)^2 + (\Delta H^*)^2 + (\Delta L^*)^2]^{0.5}$$

where

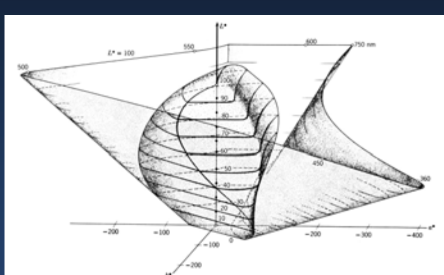
$$C^* = [(a^*)^2 + (b^*)^2]^{0.5}$$

$$\Delta H^* = [(\Delta E^*)^2 - (\Delta L^*)^2 + (\Delta C^*)^2]^{0.5}$$

Structure of CIELAB Space



Object color solid in L* a* b* space



Regularities in Data

Analysis of several sets of visual data revealed various regularities, deviating from CIELAB and more or less pronounced in different sets:

- Unit contours are ellipsoids (hue superimportance)
- Hue and lightness crispening effects
- Spacing of hue differences around the hue circle
- Tilt of ellipses of blue colors in the *a*b** diagram
- Unit contours near the neutral point are also elongated.

CMC (l:c) Formula

- Developed in mid-1980s in England based on textile sample perceptual data.
- Puts variable weights on CIELAB lightness, hue, and chroma differences.
- Standardized by ISO and AATCC among many organizations.

$$\Delta E_{CMC(l:c)} = \left[\left(\frac{\Delta L^*}{lS_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{cS_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{S_H}\right)^2\right]^{1/2}$$

where

$S_L = 0.04097 L^*/(1 + 0.01765L^*)$

unless

$L^* < 16$, then

$S_L = 0.511$

$S_C = \{0.0638\, C^*_{ab}/(1 + 0.0131\, C^*_{ab})\} + 0.638$

$S_H = S_C\,(TF + 1 - F)$

$F = \{(C^*_{ab})^4/[(C^*_{ab})^4 + 1900]\}^{1/2}$

$T = 0.38 + |0.4 \cos(h_{ab} + 35)|$

unless h_{ab} is between 164° and 345°, then

$T = 0.56 + |0.2 \cos(h_{ab} + 168)|$

l and *c* weights

- Separate weight factors allow adjustment of the influence of calculated lightness or chroma difference in total color difference.
- For textile samples (structure effect) a weight of 2 for *l* found to give best results.
- Weights of 2 for *l* and 1 for *c* are standard in ISO and AATCC:
- Formula known as CMC(2:1).

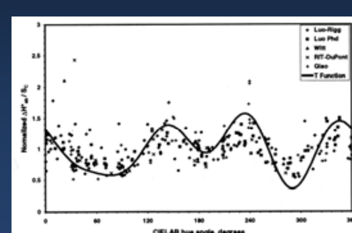
Adjustments in Different Formulas

Adjustment	Formulas CIELAB	CMC	CIE94	CIEDE2000
cube root	yes	yes	yes	yes
S_C	no	yes	yes	yes
S_H	no	yes	yes	yes
S_L	no	yes	no	yes*
T function	no	no	no	yes
R_T	no	no	no	yes
G function	no	no	no	yes

* for one gray surround only

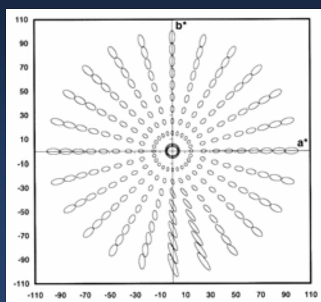
T function

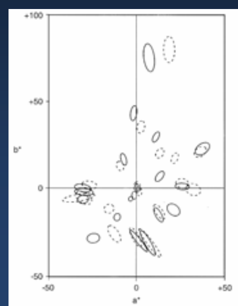
- Adjusts CIELAB hue differences to be in better agreement with perceptual data.



CIEDE2000 T function is an average of results from several data sets.

Unit ellipses in *a**, *b** plane with five of the six adjustments made by the new CIEDE2000 color difference formula



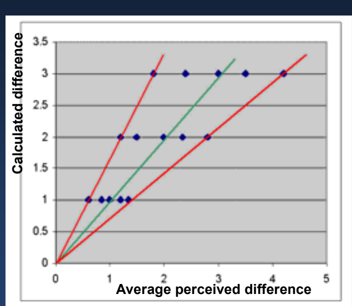


CIEDE2000

- CIEDE2000 is applicable to the 10° observer and illuminant D65, a gray surround of *L**=50, and differences from 1 to about 6 units. It is less accurate for other conditions.

- The accuracy of CIEDE2000 for average judgments under above conditions is about 65%. When compared to judgments of individual observers the accuracy might be higher or (mostly) lower.

What does 65% accuracy mean?



Example

CIEDE2000 vs. CMC for textile samples

In field tests with textile samples CIEDE2000 has not performed statistically better than CMC (2:1).

Replacing a formula industry-wide only makes economic sense if it performs demonstrably and significantly better.

AATCC RA36 has requested a moratorium on standardizing the new formula until significant improvements have been demonstrated.

5 Color difference formulas

Why Disagreements with Formula ?

• Individual differences in judgments for several reasons.
  - differences in color perception
  - learned biases

• Different surround conditions.

• Differences in test method.

• Perhaps other, as yet unknown, factors.

Conclusions

• CIEDE2000 formula has not been shown to offer statistically significant improvement for textile samples over CMC (2:1).

• An improved formula depends on
  - a better basis formula than CIELAB
  - reliable, replicated scaling of small supra-threshold differences

• Clarification of the reasons for the considerable variation in different visual small difference data sets.

Why color difference calculation?

• Despite accuracy of only 65%, calculated color differences have clear advantages in many situations over quality control by visual inspection only.

• When comparing its results against visual observations it is important that the latter are done under conditions which are comparable to those represented by the formula in use.