The Color Between Two Others

Ethan D. Montag
Munsell Color Science Laboratory, Chester F. Carlson Center for Imaging Science
Rochester Institute of Technology, Rochester, New York

Abstract

A psychophysical experiment was performed to determine the color that had the appearance halfway between two other colors with equal chroma and separated by either 40º or 60º of hue angle. Four color centers were used and a QUEST threshold procedure was employed to find the midpoint between two flanking colors. Rather than choosing colors that shared the same chroma attribute as the flanking color pair, observers chose colors that had less chroma and were closer to the midpoint of the line connecting the flanking pair in Cartesian coordinates. In a separate control experiment using the same stimulus configuration but a different set of instructions, subjects determined the color between the flanking colors that had the same chroma. In this experiment, subjects were able to choose the color with the same chroma as the flanks. The results of this experiment are discussed in relation to the usefulness of defining color appearance attributes.

Introduction

This investigation starts by asking the simple question: On which color appearance attributes would observers base their choice of color that has the appearance halfway between two others? To make this question more tractable experimentally, the following scenario is proposed. Given a plane of constant lightness in a hypothetical ideal color appearance space, we choose two colors of constant chroma, C, separated by a hue angle Δh. These two colors are called the flanks. The observer's task is to choose the color that has the appearance that is halfway between the flanks. If we assume that the hue varies uniformly in this space, then we can limit the observer's choice to a vector of constant hue and variable chroma that is between the two flanking colors. This is illustrated in Fig. 1.

Fig.1 shows the two flanking colors, F1 and F2, with a chroma of 35, separated by a hue angle of 60º. The dashed line represents the line of constant hue and increasing chroma along which the observer can choose the in-between color. There are two possible choices that can be predicted based on the validity of this hypothetical color appearance space. One possible solution is that the observer chooses point C1, which is the geometric midpoint between the two flanks. Another possibility is the observer chooses point C2 that shares the chroma attribute with the flanks completing a series of constant chroma similar to three consecutive colors in the FM 100-Hue test.[1]

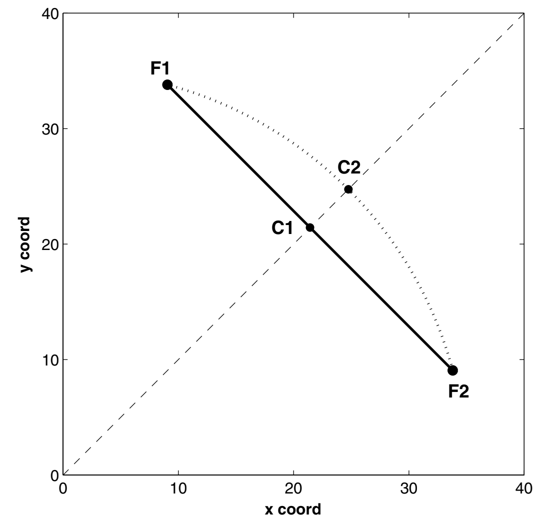

Figure 1. C1 is the color between F1 and F2 geometrically but C2 shares the same chroma attribute.

We will call the solution at point C1 the "geometric solution" and the solution at C2 the "chroma solution". Given such a space, the distance between these two solutions is given by the following equation:

$$distance = C - C\cos(\Delta h/2) \qquad (1)$$

where C is the chroma of the flanking colors and Δh is the hue angle between the flanks. In this example the distance between C1 and C2 is 4.69 units.

Of course there are other possible solutions. Observers may choose a color that is somewhere in between these two extremes. If observers behaved like Maxwell's spinning disks, they may choose a color with the intermediate chromaticity. (Because appearance spaces are typically non-linear transformations of chromaticy space, this solution will likely not fall on the constant hue line so they may have to choose the closest color on this line.)

Real color appearance spaces may or may not have the properties of this theoretical ideal color appearance space. This ideal space has perceptually uniform radial hue spacing and circular contours of constant chroma. There is no theoretical reason to expect that color appearance space with cylindrical polar coordinates of lightness, hue and chroma should be perceptually uniform. We can observe this in the divergence between the development of color difference equations and color appearance spaces.[2]

Methods

Observers were presented with stimuli consisting of two flanking color patches of equal chroma and two central color patches of equal hue and different chroma. The colors were arranged as shown in Fig. 2.

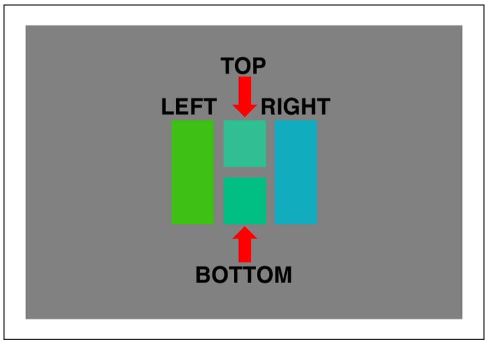

Figure 2. Stimulus arrangement

Observers indicated their choice by clicking on the patch. The patches were viewed in a darkened room on a Silicon Graphics 1600SW flat-panel LCD monitor at a normal viewing distance so that the width of the patches subtended a visual angle of approximately 1.25º. A white border set to D65 defined the white point used in the experiment. The D65 background was set at to CIELAB value of L* = 50 based on this white point. The monitor was characterized using the LCD model described in ref. 3. The experiment was run using the Psychophysics Toolbox in MATLAB.[4,5] In addition, spatial dithering was used to create the test patches and flanking colors so that 9 bits per channel precision was used in displaying the colors.

Table I: Hue, lightness, and chroma coordinates of the color centers.

		CC1	CC2	CC3	CC4
IPT	Hue	45	135	225	315
	Lightness (Ix100)	65	65	65	65
	Chroma (x150)	35	35	35	35
CIELAB	Hue (h)	~47	~142	~230	~322
	Lightness (L*)	~69	~70	~65	~64
	Chroma (C*)	~32	~40	~33	~40
CIECAM02	Hue	~44	~146	~220	~316
	Lightness (J)	~71	~70	~65	~66
	Chroma	~24	~33	~36	~33

The IPT color space[6] was chosen for the specification of the stimuli used in this experiment due to its hue linearity and uniformity. There were four color centers, h = 45, 135, 225, 315, used in the experiment all at a chroma of 0.23 which corresponds roughly to a chroma of 35 in CIELAB and a lightness, I = 0.65. The flanking colors were chosen around these color centers. Two flanking distances were used: ±30º and ±20º which will be referred to as the wide and narrow flanks, respectively. Table I shows the specification of the stimuli in IPT, CIELAB, and CIECAM02 coordinates. As will be seen in the results, the constant lightness and chroma values in IPT do not translate to constant values in CIELAB and CIECAM02. The values shown in the table show the approximate hue, lightness, and chroma values of the region corresponding to the region between C1 and C2, the flanking colors in Fig. 1, for each color center.

In the first experiment, which we will dub the "between" experiment, the observers' task was to choose which of the two square patches, top or bottom, had an appearance that was closer to being half way between the color of the left and right flanks. On each trial, a QUEST routine[7] selected a target chroma value. The colors of the two test patches were made by increasing and decreasing this target value by ±3 units of chroma (IPT units x 150). The choice of the test color with the higher chroma indicated that the target chroma value was too low. Likewise, the choice of the lower chroma test patch indicated that the target chroma value was too high. The QUEST routine determined the 50% threshold where the higher and lower test was chosen at an equal rate so that the chroma of the target color was the half-way point between the flanks.

In the second control experiment, the "chroma" experiment, the subjects' selection criterion was different although the stimuli were identical to the first experiment. In this experiment subjects were instructed to choose the patch that had a chroma that was closer to the chroma of the two flanking patches. Here the threshold determined the color that had the same chroma as the flanks. Subjects were presented with a definition of chroma and an example chroma series from the Colorcurve® Student Education Set.

Sixteen (12 males and 4 females, 9 experts and 7 novices) and eighteen color normal observers participated in the "between" (13 male and 5 female, 11 experts and 7 novices) and "chroma" experiments, respectively. One threshold value was determined for each of the color centers at both of the flanking distances so that 8 thresholds were collected per observer per experiment. Each threshold value was determined by a series of 50 trials so each observer viewed 400 trials in a session that lasted less than 1 hour for each experiment. The trials of the 8 series were randomly intermixed and the positions of the flanks and test patches were randomized. One observer, EDM, ran each experiment 4 times to get an indication of the intra-observer variability.

Results

Figure 3 shows the results for the 4 experimental runs of observer EDM in the IPT space for the "between" experiment. The figure shows the location of the flanks as closed symbols. The downward pointing triangles are the thresholds for the wide flanks and the upward pointing triangles show the results for the narrow flanks. The same data is shown in an alternative representation of IPT space where hue is plotted on the abscissa and chroma is plotted on the ordinate in Fig. 4. In this representation, the straight line connecting F1 and F2 in Fig. 1 now plots as the curved dashed lines. The constant chroma contours are now straight lines.

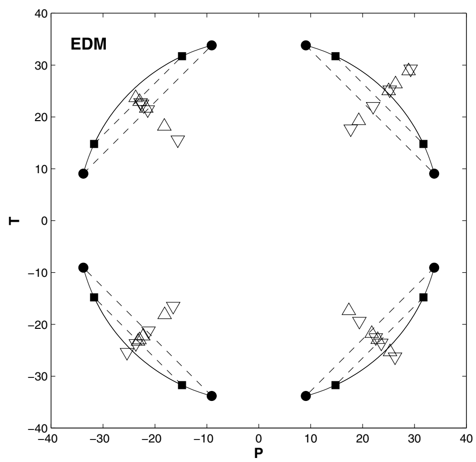

Figure 3. Results of 4 runs for EDM in IPT space. ▽ Results for wide flanks. △ Results for narrow flanks. Data is represented as in Fig. 1.

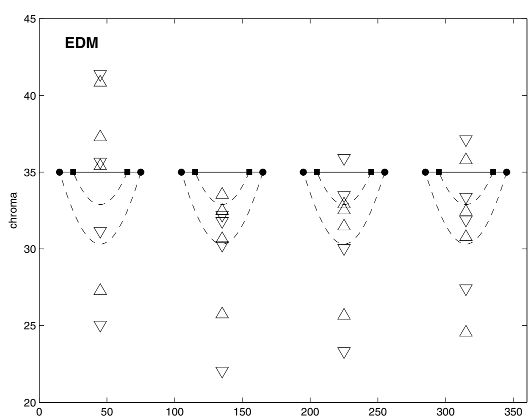

Figure 4. Hue vs. chroma representation of the results of 4 runs for EDM in IPT. ▽ Results for wide flanks. △ Results for narrow flanks.

Figures 5 and 6 show the contours for CIELAB and CIECAM02 (J, a, b) space. These figures are shown to demonstrate the differences in the coordinates of the flanks and the constant IPT chroma loci in these other spaces.

Clearly the distances between the geometric and chroma solutions are different in the different color spaces. Table II shows the distances between the geometric and chroma solutions in CIELAB and ΔE_{00} units and in units of the IPT and CIECAM02 appearance spaces. To summarize and enable a comparison among the different color spaces and color difference metrics, an index was created which represented the thresholds in terms of these differences. This index is scaled so that the geometric solution has an index value of 0 and the chroma solution has an index value of 1. Thresholds with lower chroma than the geometric solution (below the curved lines in Figs. 4, 5 & 6) have negative values and values greater than one represent thresholds that have chroma values greater than the chroma solution (above the straight lines in Figs. 4, 5, & 6).

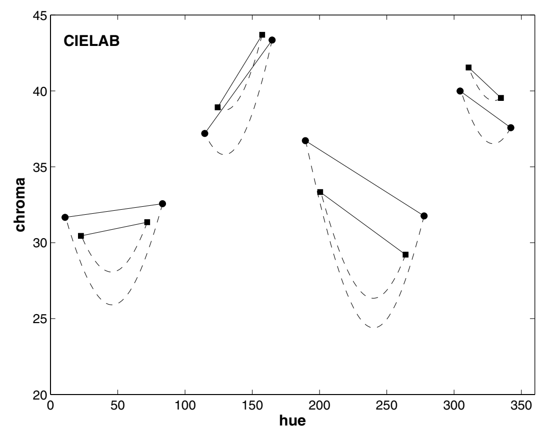

Figure 5. Hue vs. chroma loci in CIELAB space.

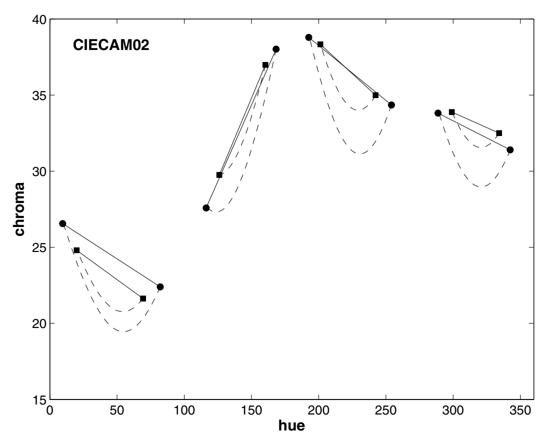

Figure 6. Hue vs. chroma loci in CIECAM02 space.

Table II: Distances between the geometric and chroma solutions.

	ΔE^*_{ab}	ΔE_{00}	IPT units (x 150)	CIECAM02 units
	Wide flanks			
CC1	6.21	2.75	4.69	4.91
CC2	4.00	1.57	4.69	4.03
CC3	9.81	4.26	4.69	5.28
CC4	2.11	0.81	4.69	3.57
	Narrow flanks			
CC1	2.82	1.24	2.11	2.22
CC2	1.85	0.71	2.11	1.82
CC3	4.80	2.11	2.11	2.41
CC4	0.92	0.34	2.11	1.57

Figures 7 shows the average results for all 16 observers (including only the first set of data for EDM) using the calculated index values for the "between" experiment. The error bars are ±2 SEM. In general the threshold index values are closer to the geometric prediction with index values closer to zero than to one. There were no significant differences between male and female observers and novices and experts.

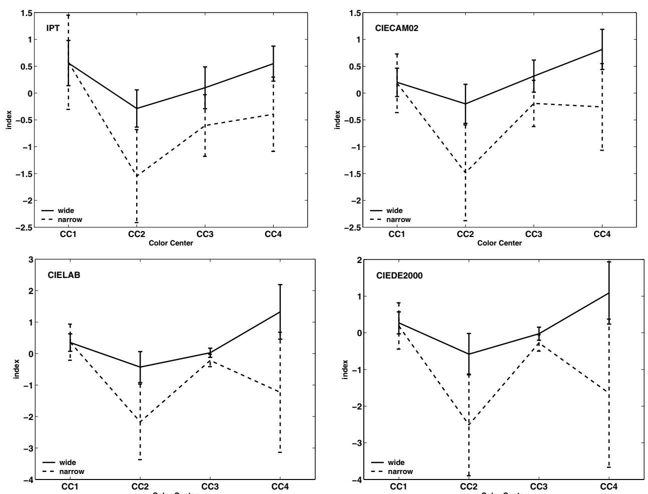

Figure 7. Average index values for the "between" experiment for each color center in IPT, CIECAM02, CIELAB, and CIEDE2000.

Figure 8 shows the results for the "chroma" experiment. Here we see that the index values are closer to 1 indicating that the subjects are able to equal chroma in close agreement to the different color spaces.

As a control experiment, this indicates that the observers were performing different tasks in the two experiments and that the color perceived as intermediate color between the two flanks is not the color with the same (or average) chroma of the flanks.

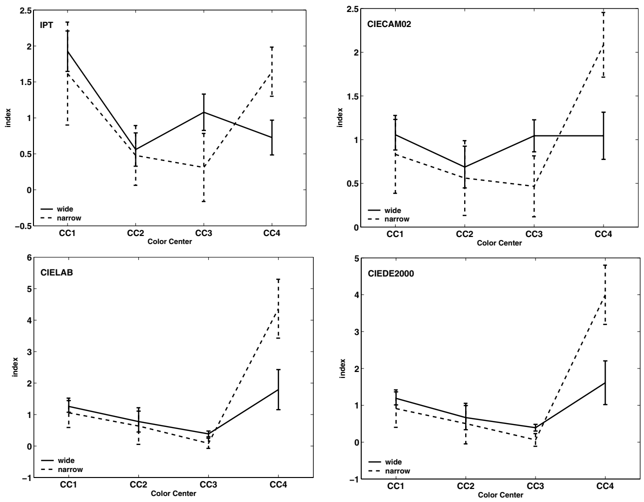

Figure 8. Average index values for the "chroma" experiment for each color center in IPT, CIECAM02, CIELAB, and CIEDE2000.

Figures 9 and 10 shows the average across the four color centers (±2 SEM) for the "between" and "chroma" experiments, respectively. Again, we see in Fig. 9 that subjects chose colors with lower chroma values than the flanks as having the appearance halfway between them supporting the geometric solution. In Fig. 10, we see that subjects can judge equal chroma fairly well with index values close to 1. It is clear that although subjects can abstract the attribute of chroma in this task, this attribute is not the salient attribute for judging which color is intermediate to two others.

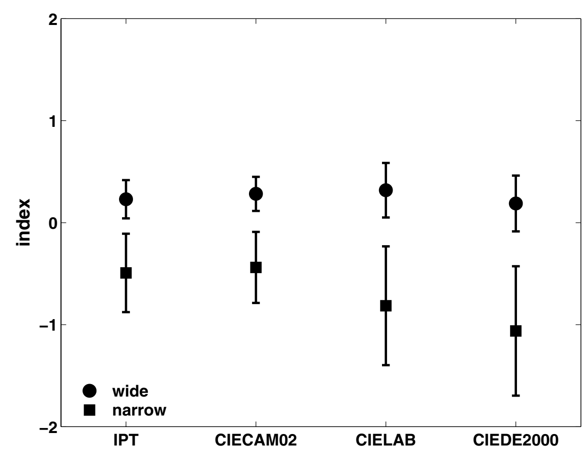

Figure 9. Average index values for the wide and narrow flanking distance for each color metric for the "between" experiment. Error bars are ±2 SEM.

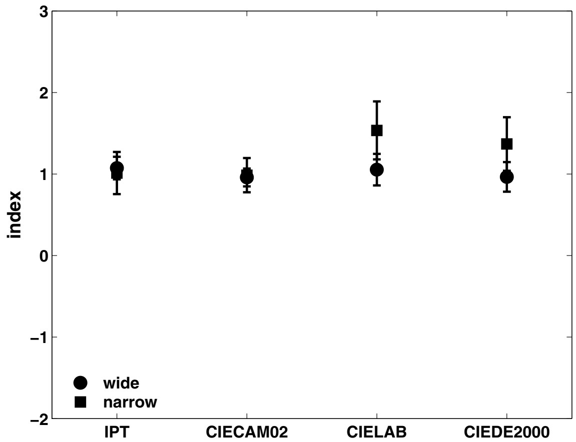

Figure 10. Average index values for the wide and narrow flanking distance for each color metric for the "chroma" experiment. Error bars are ±2 SEM.

In the "between" experiment, there are larger differences between the narrow and wide flanking distance with smaller index values associated with the narrow flanks. As the flanks become closer together the difference between the chroma and geometric predictions becomes smaller. There is not enough evidence in this experiment to determine whether this difference is due to a criterion change in selecting the in-between color as the flank distance changes. In addition the range of values, indicated by the error bars is larger in the "between" experiment than in the "chroma" experiment. This can be seen more clearly in Figs. 11 and 12 which show the variability (2 SEM) for each color center and flank distance for the "between" and "chroma" experiments, respectively. As in the previous figures we can see that the appearance spaces (IPT and CIECAM02) track together as do the the two color difference metrics (CIELAB and CIEDE2000). The two color appearance spaces also demonstrate less variability on average. This may be an indication of a more uniform scaling of chroma in these appearance spaces as opposed to the color difference metrics CIELAB and CIEDE2000. In addition we see more variability in the narrow flank data. This is likely do to the fact that the index metric represents a smaller distance for the narrow flanks, which magnifies the variability.

The variability is approximately twice as large for the "between" experiment than the "chroma" experiment. The within subject variability for observer EDM (not shown) is approximately the same size as the between subject variability and also demonstrates this difference. This increased variability in the "between" task indicates that this judgment is more variable and perhaps is a more difficult task to perform. Subjects may either have less experience or a lower degree of access to this percept compared to the equal-chroma judgment for the "chroma" experiment.

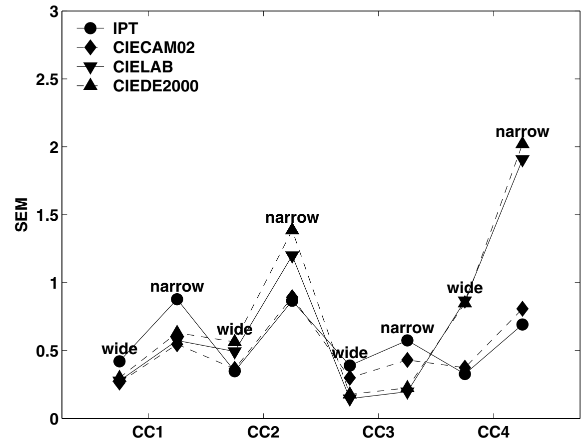

Figure 11. Variability of response in the "between" experiment.

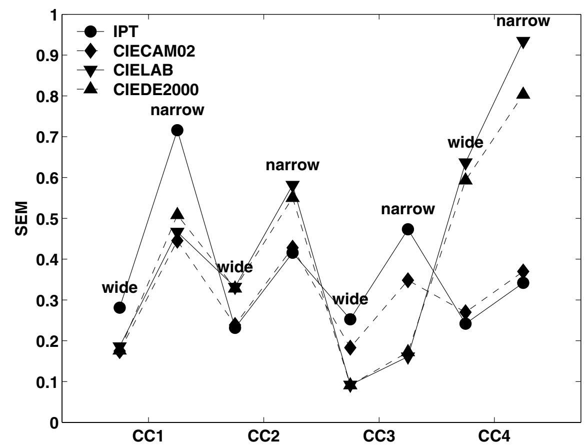

Figure 12. Variability of response in the "chroma" experiment.

Discussion

Given the appearance attributes of two colors, hue and chroma, one might expect that the color with the appearance half way between these two colors would have the intermediate hue and chroma. To test this idea, an experiment was performed in which observers had to determine the color that was intermediate in appearance to two flanking colors with the same chroma but separated in hue by either 40º or 60º. The results showed that observers do not base this judgment on the chroma attributes but select a color that is more like the geometric midpoint of the flanking colors. In a control experiment, it was shown that observers can choose a color that has the same chroma as the flanks. This implies that the color attribute of chroma is not used to determine the intermediate color between two others.

The increased degree of within and between observer variability seen in the "between" experiment as compared to the "chroma" experiment may reflect that the perceptual task itself may not be one that observers are well suited at performing either because of inexperience or its inherent difficulty. However, the results, on average, indicate that the color between two others is not the same as the color with the average chroma.

These results may or may not be surprising but they do beg the question: What is the color attribute of chroma good for? From these results we can say one thing: it not good for choosing the color between two others.

Color appearance spaces are developed as useful tools for defining colors for practical application such as cross media color reproduction or color reproduction under different adaptation conditions. The concept here is simple. Given a set of conditions, we can compute a device independent set of coordinates for the color that represent its appearance and use these coordinated for subsequently presenting the identical appearance under a different set of conditions. But do we really need color attributes to do this? It could be argued in the extreme that we do not necessarily need to know the appearance of the color to reproduce it. All we need is chromatic adaptation transforms that map the colors to a stable coordinate system. There is no need to know what the dimensions of this system represent unless the goal is to produce color rather that to reproduce color.

But to be practical, we do want to know what colors look like. Consequently much effort is put into making color appearance spaces with coordinates that have perceptual meaning. So the next question is: Are the perceptual attributes that color science has defined perceptually relevant to the way people really perceive color? The common attributes, hue, chroma, lightness, colorfulness, brightness, and saturation, are taught as underlying the perceptual organization of color. Although it is true we can use these terms to organize color and describe color, it may also be true that these dimensions may not be well related to the way color is psychologically represented. (For example, despite its importance[8] many of us only have an intellectual appreciation of the difference between chroma and saturation and would be hard pressed to select the appropriately colored stones, as in the "desert island" experiment[2] to illustrate the difference.) By analogy, these dimensions may be like the points on the compass: north, south, east, and west. Without a reference location or a compass in hand, these directions are not useful. Without the stable reference, we navigate better using left, right, forwards, and backwards.

Melgosa, et al.[9] demonstrated that even for experienced observers, discernment of the color attributes of hue, lightness, and chroma, is quite difficult in a task in which observers had to determine which attribute pairs of colors differed by or shared using colors selected from the Munsell Book of Colors. They write, "If experienced observers do not achieve the 100% correct score, it should be hypothesized that the Munsell classification is not perhaps the best perceptual or cognitive classification, and that the attributes Value, Chroma, and Hue are intermediate attributes between sensation and cognition."

Another consideration of color appearance spaces is the definition of the conditions that are necessary and sufficient for defining a space. It is likely that defining a space based on color appearance attributes does not lead to a space that is perceptually uniform in the different dimensions. For example, defining orthogonal directions based on the Hering opponent-colors will lead to non-uniformities in hue spacing. A three dimensional space may not be sufficient for representing all the necessary attributes of color especially given color appearance phenomena[10] such the Helkholtz-Kohlrausch effect, the Bezold-Brücke hue shift, the Hunt effect, etc., without additional computations that negate the value of having color space represented as a three dimensional solid.

It is possible that there are multiple psychological representations of color that are organized in a hierarchical structure with different accessibility for different tasks. At the lowest levels of the hierarchy exist the trichromatic and early color-opponent processing of color, which we cannot access consciously but can be measured psychophysically. The next higher levels may consist of the Herring opponent-colors (red-green, blue-yellow, dark-light) that underlie basic color appearance. Hue, chroma, and value can be thought of as a higher order cognitive organizational scheme for colors. For color memory and linguistic purposes, a higher level of categorical color may exist.

The results of this experiment do not tell us how color is represented but they do imply that we do not average the attributes of hue and chroma when determining the color between two others. One possible criticism of this experiment may be that the task itself is ill defined. What does choosing a color that is half way between two others mean? Even is this is true, this in itself is relevant to the understanding of color appearance and color appearance spaces. Clearly if there is a geometric representation of colors, the relative location of colors must have some perceptual relevance.

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Biography

Ethan D. Montag received his Ph. D. in Experimental Psychology in 1991 from UCSD working in color vision. He is an Assistant Professor at RIT's Center for Imaging Science where he pursues work in color science in the Munsell Color Science Laboratory. His current interests include image quality, color gamut mapping, color vision, color tolerance measurement and the use of color in information display. Dr. Montag is a member of OSA, ICVS, ISCC, and IS&T.