Freedoms and Constraints in Color Vision

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This is a brief summary of an analysis of the dimensions of color space and psychophysical evidence supporting its validity as a model of color perception. The model predicts that color perceptions must be determined in the vicinity of points in the image where there are at least three mutually bounding colored patches. In addition, the model predicts that for a trichromat there are four independent channels from color information at the receptor level. This implies that there must be some degree of interconnection among the three photopigment systems of a trichromat. The fourth channel proposed is referred to as a brightness channel.

Newton originally stated that the color perception of trichromats can be modelled geometrically as a three-dimensional barycentric space. The retina of a trichromat contains three different photopigments, each apparently in a separate type of cone. Similarly, a dichromat, whose retina contains two photopigments, has color matchings which can be modelled as a two-dimensional space. The color perception of a monochromat can be modelled as a one-dimensional space.

The method of analysis is similar to that used by J. W. Gibbs in his phase-space analysis of systems with many degrees of freedom. The following statements outline its application to color perception: A color or set of colors can change in a specific number of independent ways, or degrees of freedom, in color space. The number of independent measurements issued by the receptors (cones) when stimulated by a visual image represents the number of independent constraints on the degrees of freedom. In order to determine uniquely a color or set of colors, there must be as many or more independent constraints as there are degrees of freedom.

There are a few statements about the operating conditions of light stimulus composing a visual image and the nature of the receptor responses to light stimuli which have direct importance to this model.

The visual system evolved with sunlight as the major source of illumination in the physical world. Sunlight consists of a fairly even distribution of wavelengths in the visible light range. The surfaces of objects reflect sunlight; these generally broad-banded reflectances make up the various patches of light forming an image of the world on the retina.

The receptors operate over a range of ten decades of light intensity, although at any given time they have an ogival operating range of approximately three decades. The adaptation of the photopigments to the average light intensity determines the receptor operating range. Any information about the absolute intensity of light in the image is lost at the receptor level due to adaptation.

In addition to the relatively slow process of photochemical adaptation, the receptors have a faster type of adaptation. An image stabilized on the retina vanishes completely within four seconds. The image is kept visible by the constant jittering and microsaccades of the eye displacing the image with respect to the receptors. Experiments of this type suggest that color information about a patch in the image is obtained at its boundaries with surrounding patches.

The two types of adaptation characterize the nature of the "measurements" issued by a receptor: A receptor reports changes in the stimulus light distribution. Its sensitivity to changes is modified by the running average level of intensity of the image. In other words, the measurement issued by a receptor as it is moved from a patch in the image across a boundary to another patch will be the ratio of its response to each of the patches, as given by the Weber-Fechner Law.

The image of the physical world has three basic local configurations--patches, boundaries between patches, and three or more patches meeting at a point to form a vertex. Most of these vertices are third-degree. Higher-degree vertices rarely occur, but any image with no vertices represents a world lacking in depth. A textured surface is made up of a complex of patches, boundaries, and vertices.

If there are W mutually bounding, colored patches seen in a local configuration in the image, and there are N independent qualities for each color (hue, saturation, and brightness) in the retina, then there are WN degrees of freedom in the description of that configuration in color space. Since the brightness of a color is normalized (for one cannot imagine or see a bright yellow surrounded by much brighter reds and greens), the number of degrees of freedom is constrained by one, leaving WN-1 degrees of freedom in color space.

Among the W patches in the local configuration, there are W-1 independent ratios measured by a single receptor type. If there are N types of receptors, then there are a total of N(W-1) independent measurements. For $N > 1$ the colors of the patches cannot be uniquely determined, since there are more degrees of freedom than there are constraints.

However, in addition to the N different photopigments, there are N-1 independent combinations of the N photopigments. A ratio of the response of a combination of the photopigments is an independent measurement; that is, it cannot be determined from the ratios measured by the separate photopigments. Such a combination will be called a brightness measurement. Given one such combination, there will be a total of (N+1)(W-1) independent measurements in a local configuration of W patches.

The reports of subjects during a trichromatic color matching experiment support this analysis and the existence of a brightness measurement system. In

this experiment the visual image consists of three patches, three boundaries, and two third-degree vertices. As the observer approaches a color match, the image becomes two patches, a single boundary, and no vertices. The analysis predicts that in an image containing only boundaries, colors are underconstrained for a trichromat. As the observer approaches a color match in the experiment, the color of the matched patch and the background vary, although the match itself is invariant. This variation in observed color is not reported in a dichromatic color matching experiment.

A similar experiment where two patches are matched for brightness independent of saturation and hue supports the existence of a brightness channel. In this case there are eight degrees of freedom and only seven independent constraints, since the brightness ratio between the two patches is unity. The observed instability in this experiment forced researchers to abandon this method of brightness matching.

References

A more extensive version and bibliography of this work appears in:

(1) Linden, L. L., and Lettvin, J. Y., (1975), Evolutionary constraints on the dimensionality of color space, *Research Laboratory of Electronics Progress Report*, 116: 288-302.

(2) Linden, L. L., and Lettvin, J. Y., Freedoms and constraints in color vision (in preparation).

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