# Color and Brightness: Contrast and Context

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## Introduction

This paper is about human perception of color and brightness. It is well known that a light of a given spectral energy distribution can produce many alternative percepts depending on other lights nearby or viewed previously. Consider, for example, a patch of light that appears white when viewed against a dim achromatic background. The same patch appears charcoal gray when viewed against an intense background. Varying the background also affects color perception. A patch that appears orange against the dim background is perceived as brown on the intense one. Typically, the influence of background light on color or brightness is inferred from measurements of the change in appearance of one light (a patch) caused by introducing a second light (either a surrounding background or an 'adapting field' on which the patch is superimposed). This work has been fruitful but, as discussed below, has important limitations for understanding the color and brightness of visual stimuli composed of more than two lights.

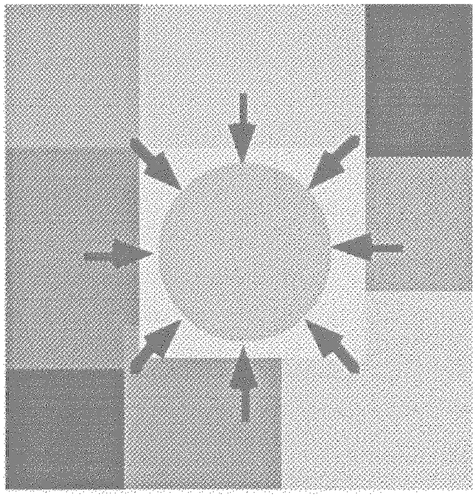

*Figure 1. The appearance of the circle depends on contrast at its boundary (arrowheads) and on context. Context is defined as light outside of the circle that is beyond the boundary.*

In natural viewing, the visual stimulus is a patchwork of many different lights reflected from various objects in view. The color and brightness of a particular uniform area can be affected by light throughout the visual scene, not just by light in contiguous regions. An important conceptual distinction can be made between (1) the change in retinal stimulation at the boundary of a uniform area, which will be referred to as *contrast,* and (2) properties of the complete visual stimulus other than the change at the boundary, which will be referred to as *context* (Fig. 1). In classical studies with only two lights (a patch and sur-round, or a patch and adapting background), the visual stimulus at the boundary is also the only stimulus outside the area of the patch (Fig. 2). Therefore contrast and context depend on the same single light and their effects are confounded. Contrast and context can be separated easily by using at least two distinct visual stimuli outside the area of the patch: one defines the contrast at the boundary and the other affects context.

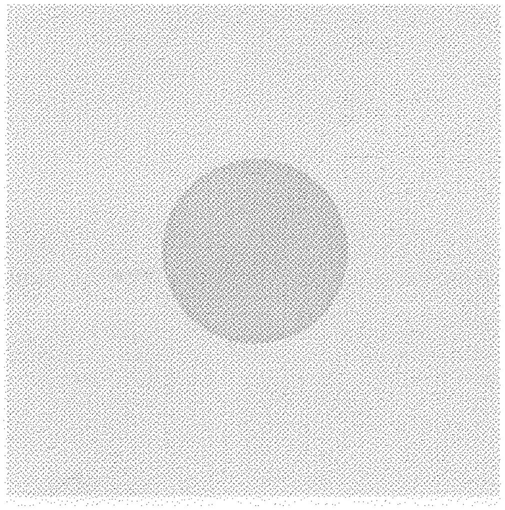

*Figure 2. With only a center and surround, contrast and context are confounded because both depend on the same visual stimulus.*

## Context

Color perception of complex scenes has been studied for centuries. Two hundred years ago, Gaspard Monge demonstrated to the Royal Academy of Sciences in Paris the dulling effect of restricting light reflected from objects in a natural scene to a narrow spectral region[1]. Chevreul' s[2] elegant investigations of color perception, about 50 years later, derived from his responsibilities as Director of Dyes at the royal tapestry works. While much has been learned since then about visual processes mediating color perception, most quantitative research has avoided stimuli with even modest complexity and focused instead on the simplest types of visual fields in which only one light influences the appearance of another[3-12] (see Wyszecki[13] for a thorough review).

Mechanisms of visual adaptation and contrast inferred from studies with simple stimuli sometimes are proposed as sufficient to explain color and brightness in more complex scenes. There is, however, broad agreement among classical theorists and modern visual scientists that they are not sufficient to account for color perception of complex scenes.[14-20]

Consider a salient example, which shows that the change in appearance of one patch of light caused by introducing additional light nearby can depend critically on whether the additional light affects contrast (at the edge of the patch) or context (at a location remote from the edge). An observer adjusts the spectral composition of a small test spot so it appears a perfect yellow (that is, neither slightly reddish nor greenish). The test light is then superimposed on a larger 660 nm 'red' adapting field. This causes the perceived hue of the test spot to change. The observer then readjusts the spectral composition of the test so that it appears a perfect yellow superimposed on the 'red' adapting field. The filled circles in Fig. 3 show how much the observer changes the test light when the 'red' adapting field is introduced. The sign and magnitude of the change (vertical axis) depend on the level of the test patch (horizontal axis). The change in the test is expressed in terms of CIE equivalent wavelength (vertical axis). These results are typical of changes in appearance caused by simple chromatic adaptation[7].

If these results are due to contrast, defined here as the change in retinal stimulation at the boundary of the test patch, then adding light some distance away from the boundary should have little effect on the test's perceived color. This can be tested by introducing a thin pencil-width achromatic ('white') ring, concentric with the test though some distance away from it while still within the larger adapting area (1° test centered on 5° adapting field, with concentric 4° thin 'white' ring). Contrary to the contrast prediction, adding the remote 'white' ring to the 'red' adapting field causes a large shift in the color of the test (open circles, Fig. 3). The change in appearance of the test due to the 'white' ring is an example of chromatic context. In some cases, introducing the 'white' ring on the 'red' background virtually counteracts the change in hue caused by the 'red' adapting light alone (see open circles near dashed horizontal line). At one test-light level, near 1.0 log td, the 'red' background alone makes the test appear greenish (filled circle below dashed line) but the 'red' background with 'white' ring makes the test appear reddish (open circle above dashed line).

A control experiment shows that the thin 'white' ring alone (no 'red' adapting field) does not alter the hue of the test. Therefore the achromatic ring in a (slightly) complex scene (that is, in the presence of a 'red' adapting field) alters color appearance of the test spot in a way that cannot be predicted from the effect of presenting the 'white' ring alone.

Many additional observations indicate the importance of distinguishing between contrast and context in complex scenes. For example, a given contextual light, such as the 'white' ring which does not affect color appearance when presented alone, can have strong and *qualitatively* variable effects in context, depending on other lights in view.[21] Another remarkable feature of contextual light is that it can be effective even when very sparsely represented (for example, random dots covering 2% of the area of a large adapting field[22]). Measurements of brightness perception show that contrast affects brightness at a different level of the visual system than context[23, 24]. Contrast depends on a monocular neural mechanism that responds to light striking the retina, while context depends on a fused binocular neural representation constructed from combining signals from the two eyes. In sum, chromatic contrast and context are important, distinct properties within a complex image, and have very different effects on the perceived brightness and color of light.

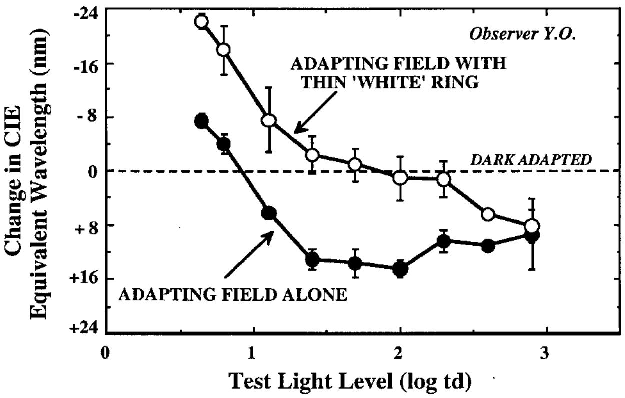

*Figure 3. The change, relative to dark adaptation, in the spectral composition of a 1° test perceived as a 'perfect' (neither-reddish-nor-greenish) yellow (vertical axis), with the test on a 5°32 td 660 nm adapting field (filled symbols) or on the same 660 nm adapting field with an added thin achromatic ring of diameter 4°. Measurements were taken over a range of test-field levels (horizontal axis). Error bars indicate ± 1 standard error of the mean.*

## Color Constancy

An important question is how chromatic contrast and context contribute to perception of objects in natural scenes. In natural viewing, most light is reflected from the objects in view. The light from an object that reaches the eye depends on the spectral reflectance of the object, and also on the spectral energy distribution of the light illuminating it. Varying the illumination can cause a large change in the reflected light that is absorbed by human photoreceptors. Yet, the perceived color of an object changes relatively little as the illuminant is varied. *Color constancy is* the perceived stability of the color of objects despite changes in illumination. While color constancy is not perfect, human color percepts are much closer to constancy than to the color expected from the light reflected from an object[25]. Recent work on contrast and context suggests some properties of the neural mechanisms mediating constancy.

Color perception depends on the light absorbed by the three types of cones. This is obvious but at the same time paradoxical, because color constancy is the capability of the visual system to extract a stable color of an object despite changes in receptoral light absorption due to changes in illumination. The resolution of the paradox is that constancy depends on receptoral responses from more than one object. Models of color constancy that depend on receptoral signals from three or more different objects have a natural connection to studies of contrast and context. This connection is best appreciated by considering fundamentals of modern models of constancy.

$$\begin{vmatrix} Q_S \\ Q_M \\ Q_L \end{vmatrix} = \begin{vmatrix} q_S(400)E(400) & q_S(401)E(401) & \ldots & q_S(700)E(700) \\ q_M(400)E(400) & q_M(401)E(401) & \ldots & q_M(700)E(700) \\ q_L(400)E(400) & q_L(401)E(401) & \ldots & q_L(700)E(700) \end{vmatrix} \begin{vmatrix} R(400) \\ R(401) \\ . \\ . \\ R(700) \end{vmatrix} \qquad (2)$$

$$\begin{vmatrix} Q_S \\ Q_M \\ Q_L \end{vmatrix} = \begin{vmatrix} q_S(\lambda_1)R_{Std}(\lambda_1) & q_S(\lambda_2)R_{Std}(\lambda_2) & q_S(\lambda_3)R_{Std}(\lambda_3) \\ q_M(\lambda_1)R_{Std}(\lambda_1) & q_M(\lambda_2)R_{Std}(\lambda_2) & q_M(\lambda_3)R_{Std}(\lambda_3) \\ q_L(\lambda_1)R_{Std}(\lambda_1) & q_L(\lambda_2)R_{Std}(\lambda_2) & q_L(\lambda_3)R_{Std}(\lambda_3) \end{vmatrix} \begin{vmatrix} E(\lambda_1) \\ E(\lambda_2) \\ E(\lambda_3) \end{vmatrix} \qquad (3)$$

A proper theory of color constancy relies on only information available to the visual system. Recent theories of color constancy take a computational approach that aims to reconstruct the spectral reflectances of objects from quantal absorptions in each of the three types of cone. The information implicit in receptoral quantal absorptions, however, is insufficient to specify exactly the reflectances of objects. Thus the information from receptors is ambiguous. Computational theories can resolve the ambiguity with assumptions about the illuminant, reflectances, and/or the human visual system.

Most computational theories of constancy seek to model the reflectances of objects and the illuminant[26-30]. These models have advanced our understanding of color constancy by showing how information available to the visual system can be used to maintain stable color percepts. They typically are silent, however, about neural processes that might carry out analogs of the computations. Studies of contrast and context can evaluate for human vision the plausibility of some assumptions implicit in these models.

To appreciate how (approximate) color constancy can be achieved, consider the light that arrives at the photoreceptors. An object with spectral reflectance function $R(\lambda)$ illuminated by a light with spectral power distribution $E(\lambda)$ reflects toward the eye an amount of light $E(\lambda)R(\lambda)$ at each wavelength. The total number of quanta per second, Q, absorbed by a photoreceptor with spectral sensitivity $q(\lambda)$ is $\Sigma_\lambda; \{q(\lambda)\, E(\lambda)\, R(\lambda)\}$. This applies to each of the three types of cone mediating human color vision (denoted here S, M, and L), so the quantal catches due to light from an object are

$$\begin{aligned} Q_S &= \Sigma_\lambda\{q_S(\lambda)\, E(\lambda)\, R(\lambda)\}, \\ Q_M &= \Sigma_\lambda\{q_M(\lambda)\, E(\lambda)\, R(\lambda)\}, \text{ and} \qquad (1) \\ Q_L &= \Sigma_\lambda\{q_L(\lambda)\, E(\lambda)\, R(\lambda)\}. \end{aligned}$$

Restricting consideration to the visible spectrum from 400 to 700 nm, the quantal absorptions $Q_S$, $Q_M$, and $Q_L$ can be written in matrix form. A 3-row by 301-column matrix relates the 301 reflectances [ R(400), R(401), .., R(700) ] to quantal absorptions. This matrix has been called the lighting matrix to emphasize its dependence on the illuminant, which is represented by the 301 power values [ E(400), E(401), .., E(700) ][31]. Different objects illuminated by the same source of light can have different spectral reflectances $R(\lambda)$ but share the same lighting matrix (equation (2)).

Consider some special cases of equation (2). Exact color constancy is possible with (i) an illuminant composed of only three monochromatic lights ($\lambda_1$, $\lambda_2$, and $\lambda_3$) and (ii) a standard reference patch of known reflectance. In this case the lighting matrix has only three non-zero columns (the columns with $E(\lambda_1)$, $E(\lambda_2)$ and $E(\lambda_3)$) so the quantal absorptions depend on only three reflectances ($R(\lambda_1)$, $R(\lambda_2)$ and $R(\lambda_3)$). The quantal absorptions for the standard reflectance patch with non-zero reflectances, $R_{Std}(\lambda_1)$, $R_{Std}(\lambda_2)$ and $R_{Std}(\lambda_3)$, can be derived from equation (2):

The known values of the reference reflectances and spectral sensitivities of cones, $q_S(\lambda)$, $q_M(\lambda)$, and $q_L(\lambda)$, can be substituted in the matrix, and then the spectral power distribution, $E(\lambda_1)$, $E(\lambda_2)$ and $E(\lambda_3)$, found in terms of the quantal catches for the reference standard. The reflectances $R(\lambda_1)$, $R(\lambda_2)$ and $R(\lambda_3)$ for any object then can be determined from the reduced form of equation (2) (only 3 non-zero columns) using the calculated values of $E(\lambda_1)$, $E(\lambda_2)$ and $E(\lambda_3)$, the known values of $q_S(\lambda)$, $q_M(\lambda)$, and $q_L(\lambda)$, and the quantal catches $Q_S$, $Q_M$, and $Q_L$ due to the object.

An illuminant composed of only three monochromatic lights is an unacceptable premise for natural viewing. The reasoning is nearly the same, however, with more realistic assumptions. Suppose, for example, all possible illuminants are some admixture of three known spectral power distributions $e_1(\lambda)$, $e_2(\lambda)$ and $e_3(\lambda)$. The power of the illuminating light at each wavelength, $E(\lambda)$, is then a weighted sum of the three components, $a_1e_1(\lambda) + a_2e_2(\lambda) + a_3e_3(\lambda)$. The advantage of the weighted-sum approach is a simplification of the problem of color constancy: only three values are required to specify the illuminant, $a_1$, $a_2$ and $a_3$ (as with an illuminant composed of only three monochromatic lights). Measurements of real illuminants suggest three values may be sufficient for many practical purposes. For example, any typical spectral distribution of daylight, which changes substantially with weather and over the course of a day, can be described very accurately by a weighted sum of three specific spectral power distributions[32].

Suppose further that the spectral reflectance of an object is some weighted sum of three known spectral reflectances, $r_1(\lambda)$, $r_2(\lambda)$ and $r_3(\lambda)$. The spectral reflectance of the object at every wavelength is then $b_1r_1(\lambda) + b_2r_2(\lambda) + b_3r_3(\lambda)$. This, too, is a fairly reasonable assumption because most spectral reflectances found in natural scenes can be described moderately well by a weighted sum of three components[33]. Color constancy would be achieved by determining $b_1$, $b_2$ and $b_3$.

Under these assumptions, the total number of quanta absorbed by the L cones is

$$\begin{aligned} &Q_L\ \Sigma_\lambda\{q_L(\lambda)\ E(\lambda)\ R(\lambda)\} \\ &\quad = \Sigma_\lambda\{q_L(\lambda)\ [a_1e_1(\lambda) + a_2e_2(\lambda) + a_3e_3(\lambda)] \\ &\quad [b_1r_1(\lambda) + b_2r_2(\lambda) + b_3r_3(\lambda)]\ \}. \qquad (4) \end{aligned}$$

Similar equations give $Q_S$ and $Q_M$. Further, the L-cone quantal absorption for a standard reference patch of known reflectance, $R_{Std}(\lambda)$, is

$$\begin{aligned} Q_L &= \Sigma_\lambda\ \{q_L(\lambda)\ [a_1e_1(\lambda)+ a_2e_2(\lambda) + a_3e_3(\lambda)] \\ &\qquad [R_{Std}(\lambda)]\} \\ &= a_1[\Sigma_\lambda\{q_L(\lambda)e_1(\lambda)\ R_{Std}(\lambda)\}] + \\ &\quad a_2[\Sigma_\lambda\{q_L(\lambda)e_2(\lambda)\ R_{Std}(\lambda)\}] + \\ &\quad a_3[\Sigma_\lambda\{q_L(\lambda)e_3(\lambda)\ R_{Std}(\lambda)\}] \qquad (5) \end{aligned}$$

The values of the terms within square brackets of the final form of equation (5) are known, by assumption. Similar equations for $Q_S$ and $Q_M$ complete a set of three simultaneous equations which can be solved for the three unknown weights of the illuminant, $a_1$, $a_2$, and $a_3$. The standard reference patch thus provides the information necessary to find the illuminant $E(\lambda)$. With the illuminant known, the quantal catch of the L cones due to a reflecting surface is

$$\begin{aligned} Q_L \quad &= \Sigma_\lambda\ \{q_L(\lambda)\ \ [E(\lambda)] \\ &\quad [b_1r_1(\lambda) + b_2r_2(\lambda) + b_3r_3(\lambda)]\ \} \\ &= b_1[\Sigma_\lambda,\{q_L(\lambda)E(\lambda)r_1(\lambda)\}] + \\ &\quad b_2[\Sigma_\lambda,\{q_L(\lambda)E(\lambda)r_2(\lambda) + \\ &\quad b_3[\Sigma_\lambda,\{q_L(\lambda)E(\lambda)r_3(\lambda)\}]. \qquad (6) \end{aligned}$$

The values of the terms within the square brackets of the final form of equation (6) are known; with similar equations for $Q_S$ and $Q_M$, these three simultaneous equations can be solved for the three unknowns $b_1$, $b_2$ and $b_3$, which give the spectral reflectance of the object.

Therefore exact color constancy is possible when (a) the illuminant is a weighted sum of three known spectral power distributions, (b) the reflectance of each object is a weighted sum of three known spectral reflectances, and (3) an object of known reflectance is identified as a reference standard[26,29]. Alternative models with somewhat different assumptions also rely on reference standards[27,28,34].

In most natural scenes there is no explicit standard patch of known reflectance but additional assumptions can eliminate the need for it. For example, it may be assumed that the average spectral reflectance over all objects in the scene has a known distribution. The known distribution is sometimes assumed to be uniform spectral reflection[34], a proposition known as the gray world assumption’. This implies the illuminant is revealed by summing the total light over the entire scene, a view that implicitly includes weighting light from each object according to its size. Alternatively, the range of lights over the complete scene may be the cue about the illuminant or, instead, an average may be taken over objects but without weighting by size. These assumptions as properties of the human visual system can be tested in studies of chromatic context, which support none of the assumptions above. Preliminary re-sults suggest these approaches are too simple because they fail to take account of the spatial frequency of light from objects[35].

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