

Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>

Contents lists available at [SciVerse ScienceDirect](http://SciVerse.ScienceDirect.com)

Vision Research

journal homepage: www.elsevier.com/locate/visres

Kirschmann's Fourth Law

J.M. Bosten*, J.D. Mollon

Department of Experimental Psychology, University of Cambridge, Downing Street, Cambridge CB2 3EB, United Kingdom

ARTICLE INFO

Article history:

Received 15 July 2011

Received in revised form 3 November 2011

Available online 19 November 2011

Keywords:

Simultaneous contrast

Color

Saturation

Asymmetric matching

Dichoptic matching

Nulling

Kirschmann's Fourth Law

ABSTRACT

Kirschmann's Fourth Law states that the magnitude of simultaneous color contrast increases with the saturation of the inducing surround, but that the rate of increase reduces as saturation increases. Others since Kirschmann have agreed and disagreed. Here we show that the form of the relationship between simultaneous color contrast and inducer saturation depends on the method of measurement. Functions were measured by four methods: (i) asymmetric matching with a black surround, (ii) asymmetric matching with a surround metameric to equal energy white, (iii) dichoptic matching, and (iv) nulling an induced sinusoidal modulation. Results from the asymmetric matching conditions agreed with Kirschmann, whereas results from nulling and from dichoptic matching showed a more linear increase in simultaneous contrast with the saturation of the inducer. We conclude that the method certainly affects the conclusions reached, and that there may not be any "fair" way of measuring simultaneous contrast.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

Kirschmann (1891) formulated a series of laws of simultaneous contrast, and the fourth of these describes the relationship between the magnitude of simultaneous contrast and the saturation of the inducer.

"Der simultane Contrast zwischen einem farbigen Eindrucke und einem Grau von gleicher Helligkeit wächst mit der Sättigung der inducirenden Farbe, jedoch nicht dieser letzteren proportional sondern in geringerem Maße, wahrscheinlich in einem logarithmischen Verhältnisse." (Kirschmann, 1891, p. 491).

"The level of contrast between a color and a grey of the same lightness grows with the saturation of the inducing field, not proportionally but to a lesser extent, probably in a logarithmic relationship."

Since Kirschmann proposed his Fourth Law, a succession of researchers has measured the function describing the variation of the magnitude of simultaneous contrast with the saturation of the inducer. They have described the function variously as linear, as increasing compressively, and as asymptoting at low background saturations. The same researchers have used a variety of methods including nulling, asymmetric matching, dichoptic matching and nulling of an induced sinusoidal modulation. A summary of these studies is given in Table 1, including methods and conclusions.

"Saturation" has been defined as the "the attribute of visual sensation which permits a judgment to be made about the degree to which a chromatic stimulus differs from an achromatic stimulus of the same brightness" (Wyszecki & Stiles, 1982). In other words, saturation is a subjective stimulus quality. However, in discussions of Kirschmann's Fourth Law, 'saturation' is usually used to refer to the objective metric according to which the inducing surround is varied. The metrics used to quantify saturation in the studies listed in Table 1 vary: Some use CIE chromaticity co-ordinates, some MacLeod–Boynton chromaticity co-ordinates, and some of the older studies use the angle of the colored component in a chromatic mixture achieved by a spinning disk. These metrics are all linear transformations of each other. The stimuli we use in the present study lie along a single ($L/(L+M)$) axis in MacLeod–Boynton (1979) chromaticity space, and we express the saturation of the inducer in terms of this axis.

As several authors have already pointed out (Ekroll, 2005; Shepherd, 1999), the variety of methods used to measure simultaneous contrast suggests that the differences in results arise from the multiplicity of methods used for measurement. It is this hypothesis we test here. We report the results of experiments performed to test the validity of Kirschmann's Fourth law using the same subjects, and the same metric for quantifying saturation, but four different methods.

In the Discussion we offer explanations for why the measurement method alters the relationship between inducer saturation and the magnitude of simultaneous contrast. We discuss the merits and drawbacks of the various methods used to measure simultaneous contrast, and conclude that measurements of the absolute magnitude of simultaneous contrast cannot be generalized beyond

* Corresponding author.

E-mail address: jmb97@cam.ac.uk (J.M. Bosten).

Table 1
Summary of previous studies.

Study	Method	Conclusion
Helmholtz (1909, translation 1924)	Observation	Desaturated inducers can have a relatively great inducing effect
Köhler (1904)	Observation	Weakly saturated colors produce more intense contrast effects than strongly saturated ones
Köhler (1904)	Nulling	Contrast increases with the saturation of the inducer, but the rate of increase falls with inducer saturation
Crane (1917)	Nulling	Contrast increases in proportion to the saturation of the background
Kinney (1962)	Asymmetric matching	The colors induced by red and yellow show no effect of the saturation of the inducer, those induced by blue and green show increasing contrast with inducer saturation
Hambrouck (1975)	Asymmetric matching	The ratio of the saturation of the inducing to induced hue ranges from very small to greater than 1
Valberg (1974)	Dichoptic matching	Contrast increases in proportion to the saturation of the inducing field
Krauskopf, Zaidi, and Mandler (1986)	Nulling a sinusoidal modulation	Contrast increases with the saturation of the inducer, but the rate of increase falls with inducer saturation (for most observers)
De Valois et al. (1986)	Asymmetric matching with a dynamic stimulus	Chromatic simultaneous contrast increases with the saturation of the inducer (but with a shallower gradient than for luminance contrast)
Brenner, Cornelissen, and Nuboer (1988)	Asymmetric matching	The level of simultaneous contrast reaches asymptote at low inducer saturations
Brenner, Cornelissen, and Nuboer (1988)	Dichoptic matching	Contrast increases with inducer saturation
Shepherd (1999)	Dichoptic matching	Contrast increases in proportion to the saturation of the background at low background saturations and increases compressively at high background saturations. When the surround is of low $S/(L+M)$ value, the relationship between contrast and inducer saturation is approximately linear

the context of each individual experiment. We also consider the implications of our results for the different theories of what causes simultaneous contrast, from Monge's hypothesis that simultaneous contrast is a result of color constancy (Monge, 1789; see Mollon, 2006), to Whittle's theory that perception of the color of surfaces on colored surrounds depends on the cone contrasts between surface and surround (Whittle, 1994a, 1994b, 2003).

2. Methods

Our experiment comprised four conditions:

- (i) Asymmetric matching where a black background surrounded the comparison patch and test stimulus.
- (ii) Asymmetric matching where a background metameric to equal-energy white surrounded the comparison patch and test stimulus.
- (iii) Dichoptic matching where the comparison patch was surrounded by a background metameric with equal-energy white, and the test patch was surrounded by the inducing background.
- (iv) Nulling where the background was modulated sinusoidally around a point metameric with equal energy white.

2.1. Stimuli

A schematic of the stimuli for the four conditions is given in Fig. 1. For methods (i), (ii) and (iii), the test patch and comparison patch were disks with diameters of 1° . The backgrounds were annuli with diameters of 8° , concentric with the test and comparison patch. The centers of the test patch and the comparison patch (for methods (i) and (ii)) were separated by 14° . In all experiments the viewing distance was 45 cm.

For method (iii) (dichoptic matching), the test patch, comparison patch and surrounds had the same diameters as in the other three methods, but the test and comparison patches were not concentric with their surrounds. Instead, the test patch and the comparison patch were displaced 1.5° horizontally from the center of their surrounds. The comparison patch had a surrounding annulus of the same dimensions as the inducing annulus. The comparison and test stimuli were perceptually fused by means of a haploscope so that the stimulus appeared to the observer as a single surround

containing two horizontally displaced patches (the test patch and the comparison patch), their centers separated by 3° .

Chromaticities were specified in MacLeod–Boynton (1979) chromaticity space. All stimuli had a luminance of $18.3 \text{ cd}\cdot\text{m}^{-2}$, and an $S/(L+M)$ co-ordinate of 0.016, the $S/(L+M)$ coordinate of equal-energy white. The inducing surrounds differed from the test patches along the $L/(L+M)$ axis, and the surrounds were either higher or lower in $L/(L+M)$ than the test patch. Sixteen logarithmically spaced surround chromaticities were tested in each condition. The chromaticity of the reference point was equal to that of equal energy white ($L/(L+M) = 0.665$; $S/(L+M) = 0.01606$). One set of surrounds ranged in saturation from $L/(L+M) = 0.667$ to $L/(L+M) = 0.725$. The complementary set of surrounds ranged in saturation from $L/(L+M) = 0.664$ to $L/(L+M) = 0.606$.

For method (iv) (nulling), the chromaticity of the surround varied sinusoidally with time at a rate of 1 Hz (De Valois et al., 1986; Krauskopf, Zaidi, & Mandler, 1986). The surround's average chromaticity and the center of its sinusoidal modulation was equal-energy white, and the extremes of the modulation were the same as the surround chromaticities in the other three conditions.

All stimuli were drawn using a Cambridge Research Systems VSG2/3 visual stimulus generator and presented on a Sony Trinitron 400PS CRT monitor. The monitor had been gamma-corrected using a Cambridge Research Systems ColorCal, and calibrated using a PR650 spectroradiometer. The monitor's frame rate was 100 Hz. All the experiments were programmed and run using Matlab. Responses were gathered from subjects with a Cambridge Research Systems CT3 response box.

2.2. Procedures

Dichoptic matching and asymmetric matching (methods (i), (ii) and (iii)): On each trial, the test stimulus was presented randomly on either the left or the right side of the screen and the comparison was presented on the other side. The stimulus was presented for two seconds, and the observer was free to give his response at any time during stimulus presentation, or during the one-second interstimulus interval. Within each block two surrounds were tested on randomly interleaved trials, with chromaticities placed symmetrically on either side of equal-energy white. This had the advantage of negating long-term chromatic adaptation.

Before each block a random number generator decided what perceptual decision the subject was required to make on that particular

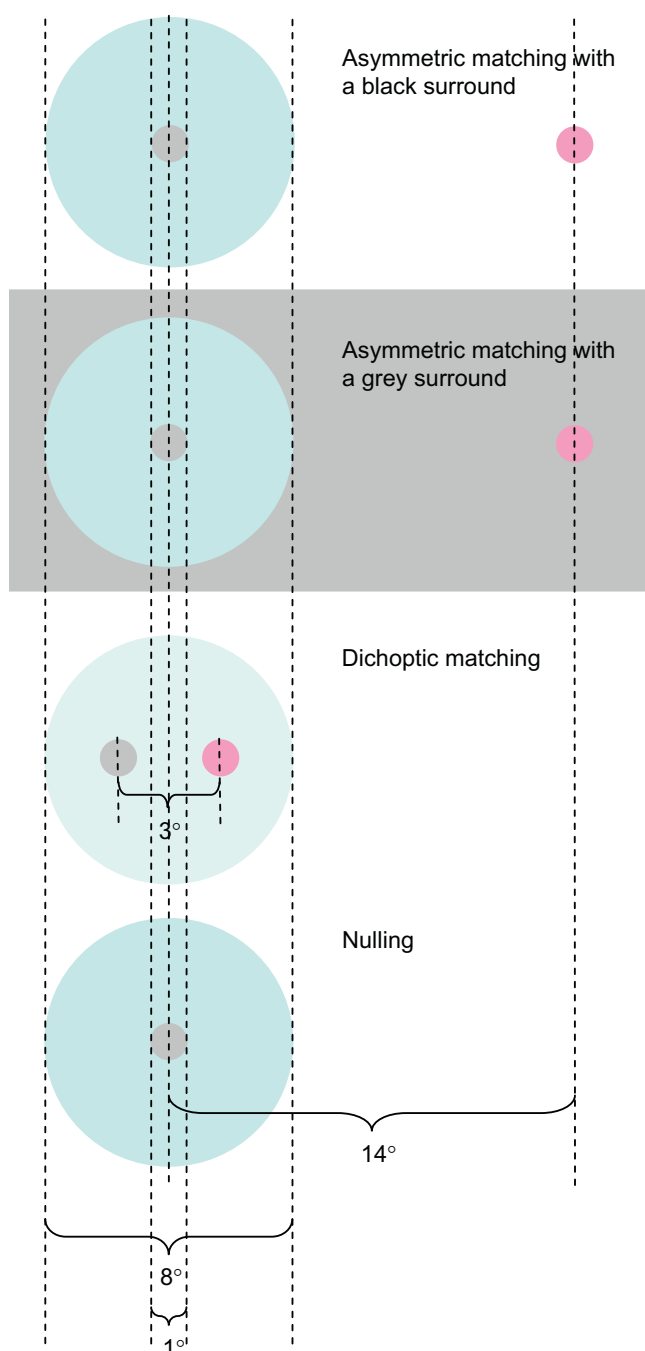


Fig. 1. Representation of the stimuli for our four methods of measuring simultaneous contrast.

block. He or she would be required either to decide which of the test and comparison patches was the greener, or to decide which was the redder. Two staircases converged on the subject's match to test patches embedded in each of the two surrounds presented in a given block, so that each block comprised 4 randomly interleaved staircases. The staircase presented on each trial was decided by means of a series of randomly generated 4×4 Latin Squares (Fisher, 1942). The initial step size was 0.014 units along the $L/(L + M)$ axis. This was reduced following the crossing of each pair of staircases by a factor of 10, and data collection began at that point.

Estimates of the subject's match points were based on his responses over the following 48 trials. For each staircase, the probability of a given response was calculated at each staircase position, and a cumulative Gaussian psychometric function was fitted using

the freely available software *psignifit* (Wichmann & Hill, 2001a, 2001b). The point of subjective equality was read off the psychometric function as the point where the subject was equally likely to give each response.

Nulling (method (iv)): The sinusoidal modulation of the inducing surround induced an apparent chromatic sinusoidal modulation of the test patch in antiphase with the surround. At the beginning of each trial the test patch modulated between $L/(L + M) = 0.605$ and $L/(L + M) = 0.725$, randomly either in phase or in antiphase with the background modulation. The observer was instructed to minimize the apparent modulation of the test patch by pressing two buttons. Each button-press changed the amplitude of the reference modulation by 0.002 units along the $L/(L + M)$ axis; one button caused an increase in the amplitude of the sinusoidal modulation in $L/(L + M)$, and the other button caused a decrease. The observer was instructed to indicate when he had found a null point with which he was satisfied. Six nulls were made for each inducing surround and a mean was taken.

2.3. Subjects

Nine subjects completed the experiment, six female and three male. Of these, six subjects had participated in one or more earlier experiments, and two were the authors. All had normal color vision, assessed using the Ishihara plates.

3. Results

Curves measured by each of the four methods, are shown in Fig. 2a. In this figure, the saturation of the inducing surround, expressed in $L/(L + M)$ value, increases along the abscissa from left to right. There are two complementary sets of data for each condition: those where the surround had a higher value of $L/(L + M)$ than the test patch, and those where the surround had a lower value of $L/(L + M)$ than the test patch. The $L/(L + M)$ values indicated on the lower x-axis are those where the surround has a higher $L/(L + M)$ value than the test patch; the values indicated on the upper x-axis are those where the surround had a lower $L/(L + M)$ value than the test patch. The central line (interspersed dashes and dots) indicates the physical chromaticity of the test patch. The ordinate indicates the $L/(L + M)$ value of the average subject's point of subjective equality for comparison and test patches. Data above the central horizontal line show points of subjective equality and nulling modulations for inducer values indicated on the upper x-axis, i.e. where the test patch had a greater $L/(L + M)$ value than the surround. Data below the central horizontal line show points of subjective equality and nulling modulations for inducer values indicated on the lower x-axis.

For further analysis we reduced the number of degrees of freedom in the data set by quantifying the magnitude of simultaneous contrast for each subject at each inducer saturation as the difference between points of subjective equality for test patches embedded in complementary surrounds with higher and lower $L/(L + M)$ values than the test patch. Fig. 2b shows the reduced data.

From Fig. 2 it is clear that the method of measurement influences the form of the function that relates simultaneous contrast to the saturation of the inducer. For asymmetric matching (gray and black curves), the magnitude of simultaneous contrast reaches a maximum at low inducer saturations. For nulling, the relationship appears to be linear. Dichoptic matching seems to be an intermediate case: the relationship is saturating, but the magnitude of simultaneous contrast keeps increasing to the edge of the range of inducer saturations that were tested.

A 4×8 repeated measures ANOVA was run with inducer saturation and condition as factors. Significant main effects of both saturation ($F_{1,63,13.0} = 30.8$, $p < 0.001$) and condition ($F_{1,69,13.5} = 7.2$,

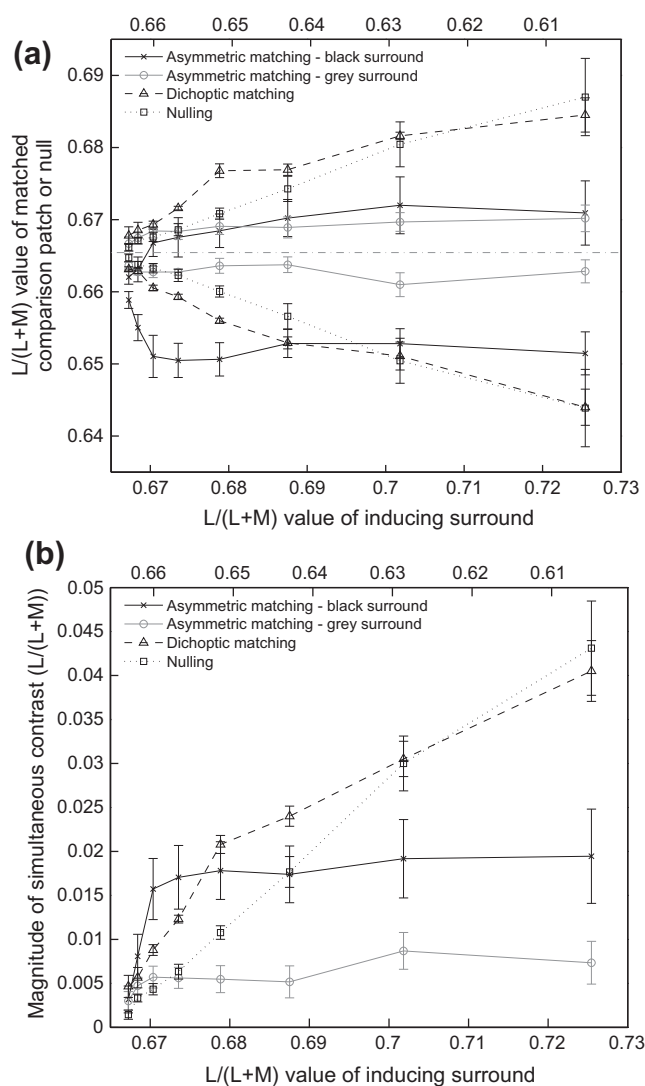


Fig. 2. (a) (Upper plot) Results for each of the four methods. Saturation increases along the abscissa. The scale shown along the lower x-axis is for surrounds of higher $L/(L+M)$ than the test patch, and the scale along the upper x-axis is for surrounds of lower $L/(L+M)$ than the test patch. This graph shows mean points of subjective equality or mean nulls for the four conditions: asymmetric matching with a black surround (solid black line), asymmetric matching with a gray surround (solid gray line), dichoptic matching (dashed line), and nulling (dotted line). The central line (interspersed dashes and dots) indicates the physical chromaticity of the test patch. Data for two complementary conditions are shown: data above the central horizontal line show points of subjective equality and nulling modulations for inducer values indicated on the upper x-axis, i.e. where the test patch had a greater $L/(L+M)$ value than the surround. Data below the central horizontal line show points of subjective equality and nulling modulations for inducer values indicated on the lower x-axis. Error bars indicate ± 1 standard error of the mean. (b) (Lower plot) shows the same data as (a), but with simultaneous contrast quantified as the difference between the two complementary conditions (i.e. for each condition, the difference between the data above the line indicating the chromaticity of the test patch, and the data below the line). The difference was taken for each subject, and the mean difference is shown in the figure. Error bars indicate ± 1 standard error of the mean.

$p = 0.01$) were found. There was a significant interaction between saturation and condition ($F_{2,29,18,3} = 7.6, p = 0.003$).

4. Discussion

Fig. 2 shows how the relationship between simultaneous contrast and inducer saturation depends on the experimental method. In general terms, our data do confirm Kirschmann's Fourth Law: For all four methods of measurement, the degree of simultaneous

contrast increases with the saturation of the inducer, 'but in a diminishing way'. However, the exact form of the function is very dependent on method. The degree of simultaneous contrast is lowest when the method is asymmetric matching and when the comparison patch has a gray surround. It is highest at low inducer saturations when the method is asymmetric matching and when the comparison patch has a black surround, and is highest at high inducer saturations when the method of measurement is nulling or dichoptic matching.

Our conclusion that the shape of the function relating simultaneous contrast to inducer saturation depends on the method of measurement may explain the disagreement in the literature over the shape of the function. However, when method is accounted for, we find we are in broad agreement with some researchers but not others. When the method of measurement is asymmetric matching, we are in agreement with Brenner, Cornelissen, and Nuboer (1988) that the magnitude of simultaneous contrast asymptotes at low inducer saturations. When the method of measurement is dichoptic matching, we agree broadly with Shepherd (1999), that contrast increases with the saturation of the inducer, but compressively at high background saturations. We disagree with Valberg (1974), who concluded that the increase in simultaneous contrast was proportionate to the saturation of the inducer.

Although Crane's (1917) method of nulling was not of a sinusoidal modulation, our own results for nulling agree with her finding that contrast increases in proportion to the saturation of the inducer. Köhler (1904; for a short review in English see Washburn, 1904) and Krauskopf, Zaidi, and Mandler (1986) concluded that simultaneous contrast increases with inducer saturation, but at a rate decreasing as saturation increases. This agrees with our findings for the other methods, but not for nulling.

What are the possible reasons for the differences we have observed in the form of the curves resulting from our different methods? Below we provide a theoretical explanation for the form of the function resulting from each method in turn.

4.1. Asymmetric matching

The major features of the curves showing data measured using asymmetric matching are as follows:

1. Simultaneous color contrast increases rapidly at low inducer saturations.
2. Simultaneous color contrast reaches an asymptote at low inducer saturations.
3. Curves for data measured when the comparison surround was gray are of a similar shape to those for data measured when the comparison surround was black, but show a much smaller simultaneous contrast effect.

Why does simultaneous color contrast appear to increase rapidly at low inducer saturations when measured with asymmetric matching? One possible explanation stems from the tradition started by Monge (1789), and continued by Helmholtz (1909, translation 1924), Jaensch (1919), Lotto and Purves (2000) and Cunthasaksiri, Shinoda, and Ikeda (2004): that simultaneous contrast is a result of color constancy. The idea is that the observer interprets the surround as a veiling illumination. If we take as an example a gray test patch in a green surround, the visual system infers that if the illuminant is green, then the test patch must be reddish in order to send to the retina the gray light that it receives. Compensating for the green illuminant by color constancy causes the perceived redward shift in the color of the patch, a shift that we call simultaneous contrast.

In a restricted situation like that of the stimulus for simultaneous contrast, the visual system has two competing hypotheses

about what the retinal stimulus corresponds to in the external world. One idea, applied in the example above, is that the test patch is reddish and under a green illuminant. The competing idea is that it is gray, surrounded by a green reflective surface, and under a neutral illuminant. What is perceived as simultaneous contrast may stem from the visual system's best guess about the external source of the retinal image. Since real-world illuminants are more likely to be desaturated than saturated, as the saturation of the inducing surround increases, the probability that the retinal image corresponds to a red test patch under a green illuminant decreases, and the probability that it corresponds to a gray test patch on a green surround illuminated neutrally increases. So the color constancy correction applied to the test patch increases rapidly when the surround has low saturation, but changes less thereafter, because little further correction is applied by the mechanisms that seek to achieve color constancy.

The idea that simultaneous contrast is a result of constancy, and that desaturated surrounds are more plausibly interpreted as reflecting the chromaticity of the illuminant, is implicit in Helmholtz's (1909, translation 1924) observation that when a piece of neutrally colored translucent paper is placed over a traditional stimulus for simultaneous contrast (for example, a gray paper laid on top of a colored paper), the magnitude of simultaneous contrast is increased. Helmholtz believed that the observer, compensating for the implied veiling illumination by "unconscious inference", interprets the patch as a surface with a reflectance complementary to the chromaticity of the veiling illuminant.

A different tradition, begun by Ewald Hering, seeks to explain simultaneous contrast as the result of low-level lateral interactions in neural channels. This has long been seen as in opposition to Helmholtz's explanation, but is not necessarily so (Bosten & Mollon, 2010; Kingdom, 1997). Lateral inhibition in low-level color channels may simply be one of the mechanisms by which color constancy is achieved. Within the Hering tradition, a low-level explanation could be given for the shape of the function relating the magnitude of simultaneous contrast to the saturation of the inducing field. Suppose that lateral inhibition acts between chromatically opponent neurons at an early stage in the visual system. Such neurons are likely to have compressive operating functions and to be most sensitive in the middle of their range (Krauskopf & Gegenfurtner, 1992; Polden & Mollon, 1980). When the response of the neuron is unpolarized and corresponds to the middle of its range, a small change in lateral inhibition would produce a large change in response; but when the response is already polarized, the same change in lateral inhibition may have little effect on the response. This explanation is not necessarily in opposition to the constancy explanation we offered above.

The difference in results between the method where the comparison surround is neutral and the method where the comparison surround is black could also, we suggest, be explained by color constancy. The introduction of the neutral background would disrupt the impression that the inducing surround reflects the chromaticity of an illuminant. The background itself, being a larger area, and perhaps a more plausible illuminant, would be interpreted as reflecting the chromaticity of the illuminant. A different explanation, however, is that in the case where the comparison surround is black, it is "free-floating" (rather than anchored in a particular chromatic context), and may therefore tend to appear achromatic. The comparison patch must then be more saturated in order to be judged colored, and matched with a given test patch.

What is the relationship of our results to the crispening effect (Whittle, 1992)? Whittle discovered that there is a reduction in luminance discrimination thresholds for two surfaces when they are both embedded in a surround of a similar luminance to themselves. He called this the crispening effect. There is an analogous crispening effect for chromaticity (Ovenston & Whittle, 1996).

Our results for asymmetric matching show a "crispening effect": the rate of change of perception of the test patch is greatest when the test patch chromaticity is nearest the surround chromaticity, at low inducer saturations. As has been suggested recently by Ekroll, Faul, and Wendt (2011), we believe that simultaneous contrast and the crispening effect are not independent effects. Instead they are words for two different behavioral measures of the same process. In the presence of a surround of similar, but distinct, chromaticity, the crispening effect is the enhanced discriminability for a given test patch, and simultaneous contrast is the coincident perceived shift of the chromaticity of the test patch in the direction away from the surround.

4.2. Dichoptic matching

The magnitude of simultaneous color contrast measured using dichoptic matching was greater at high inducer saturations than that measured using asymmetric matching. The reason for the difference between the results of the two methods might be that during dichoptic matching the two eyes are in different adaptive states. In the present study the eyes were in different adaptive states only over the course of one trial, but in earlier studies the eyes were separately adapted for several minutes (Shepherd, 1999; Valberg, 1974). Given time, von Kries adaptation (von Kries, 1878; for a translation of parts see von Kries, 1970) tends to renormalize the responses of the different classes of cone. Since, under dichoptic matching, the comparison surround is presented to one eye, and the inducing surround is presented to the other eye, there may, after sufficient viewing time, be complete von Kries adaptation for each eye separately. As a result, objectively different comparison and test patches could result in similar neural signals, because von Kries adaptation has renormalized the cone responses to the surrounds of the test and comparison patches.

Whittle (2003) has identified von Kries transformations as the mechanism behind his cone-contrast rule (1994a, 2003). The cone-contrast rule predicts that a linear function relates the magnitude of simultaneous color contrast to the inducer saturation, because color appearance, at least under some conditions of viewing (Whittle, 1994b), is decided by the cone contrast between the embedded patch and its surround. MacLeod-Boynton chromaticity coordinates are the units of the functions shown in Fig. 2, In Fig. 3 the same data are shown but transformed so that the units are cone contrasts. The cone contrasts of the comparison surround to comparison patch are plotted against the cone contrasts of the inducer to test patch. Results for only two conditions are plotted, method (ii) (asymmetric matching with a gray comparison surround) and method (iii) (dichoptic matching). The cone contrast rule does not make obvious predictions for the other two conditions, method (iv) (nulling) and method (i) (asymmetric matching with a black comparison surround). Whittle's cone contrast rule predicts that such a function would be linear and have a gradient of 1, since colors are equal if cone contrasts are equal.

Our results are in disagreement with Whittle's cone-contrast rule, and also with Shepherd (1999) who concluded that her results are "in general agreement with a cone-contrast description." In spatial arrangement, our dichoptic matching condition was very similar to Whittle's haploscopic superposed display (Whittle, 1994a, 1994b, 2003), yet the magnitude of simultaneous color contrast measured using dichoptic matching is well short of what is predicted from cone-contrast theory, except at very low surround saturations. The difference between our dichoptic matching experiment, and Whittle's, where results did conform to the cone-contrast rule, is that we randomized the eye of presentation of the inducing surround on each trial. There was therefore limited time for von Kries adaptation to progress, and we suggest that

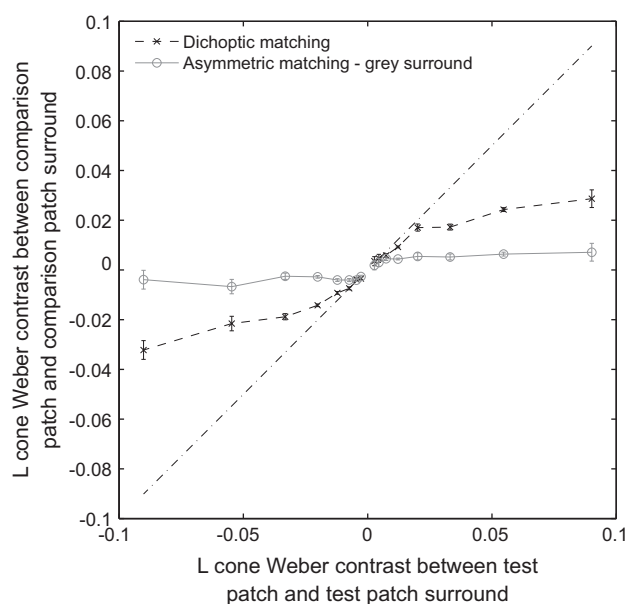


Fig. 3. Comparison with predictions from cone-contrast theory. Cone contrast theory predicts two patches should match when the cone contrasts with their backgrounds are equal. If this prediction holds, data should follow the diagonal line (interspersed dots and dashes). Results for methods (ii) (asymmetric matching with a gray comparison surround) and (iii) (dichoptic matching) are shown. Negative Weber contrasts indicate decrements, and positive Weber contrasts indicate increments. Results for both methods fall short of the prediction from cone-contrast theory, except in a very narrow region near the chromaticity of the test patch.

von Kries adaptation must be complete in order for color appearance to be determined entirely by cone contrasts.

We discussed above the tradition of considering simultaneous contrast as a result of color constancy. Von Kries adaptation is likely to contribute to color constancy. However, it takes place over time, and will not be so dominant in the type of color constancy that takes place “instantaneously” (Barbur et al., 2004; Land & Daw, 1962) when the eye is transferred between regions of differing illumination, shading or transparency. The difference in our results between asymmetric matching and dichoptic matching can be explained in these terms. Under dichoptic matching, each eye makes different judgments about the chromaticity of the illuminant. Each compensates for its implied illuminant (either the test patch surround, or the comparison surround). This has the result that simultaneous contrast will increase linearly with inducer saturation, obeying the cone contrast rule. In our dichoptic matching experiment, the level of induction fell short of what would be predicted from cone contrasts, because there was not time for complete von Kries adaptation. Under asymmetric matching, the two eyes are in the same adaptive state, and each makes the same estimate of the chromaticity of the illuminant, as discussed above.

4.3. Nulling

Of our three methods, nulling was the least satisfactory for the subject. All subjects but one reported that they were unable to find null points and instead found the point of minimum modulation. Of these, three were very dissatisfied with the task and found it difficult to decide on a single point of minimal modulation.

As subjects, the authors found that a decrement in $L/(L+M)$ relative to the background always appeared green, while an increment in $L/(L+M)$ relative to the background always appeared red. During the nulling experiment, we therefore found that any in-phase modulation of the test patch smaller in amplitude than

the surround modulation appeared to vary between red (when the surround was at its green point) and green (when the surround was at its red point). Alternatively, when the modulation of the test patch was in phase with the modulation of its surround and had the same amplitude, we found the test patch to be indistinguishable from the surround, and therefore the test patch appeared green at the surround's green point and red at the surround's red point. Our percept of the test patch appeared to flip in the range between the point when the amplitude of modulation of the test patch was one visible step smaller than that of the surround, and the point when its amplitude was equal to that of the surround.

We felt our ability to null the test patch was compromised by the fact that we perceived the test patch to be behind a colored transparency when it was modulating in phase with the surround, but with an amplitude smaller than that of the surround. When the surround was red, the test patch appeared to be green, but behind a red transparency. When the surround was green, the test patch appeared to be red, but behind a green transparency. Ekroll (2005) has made a similar observation about the difficulty of finding an achromatic point inside a chromatic surround. He described the kind of process involved in the attempt: “one finds oneself reverting to very ‘cognitive’ criteria like “Could this balance of red-dishness and greenness pass for a good grey?” or “If I disregard the red-dishness and the greenness, is this setting the one which has the most salient grey content?””

To investigate the source of participants' difficulties with nulling, Ekroll et al. (2002) measured the achromatic point on different colored backgrounds. Subjects were required to set full hue circles that were as small as possible, by adjusting the position and radius of a single circle of sixteen test patches evenly spaced in CIE chromaticity space. The four subjects were experienced psychophysical observers and they were instructed that in a full hue circle they should see each of the four unique hues: red, green, blue and yellow. A subject's achromatic point measured by this method was defined as the center of his hue circle. The loci of the hue circles found by this method were not around the point that subjects would perceive as achromatic in the absence of chromatic context, but at the chromaticity of the background. Ekroll's result may explain our subjects' difficulty with the nulling task. It is the chromaticity of the surround that is at the center of the hue circle, not the achromatic point as measured in the absence of a chromatic context. In our nulling experiment, an $L/(L+M)$ decrement appeared green and an increment red, but neither these, nor the surround chromaticity itself, necessarily appeared achromatic.

We believe that the form of our results for nulling reflects the compromise subjects were required to take during the task in deciding which complex percept to call achromatic. Most subjects chose a null that was near the background chromaticity, hence the linear function that results. However, these nulls were not satisfactory, and we are not confident that it is possible to quantify simultaneous color contrast by this method.

5. Conclusions

Differences in methodology may explain why authors have disagreed about the relationship between the level of induction and the saturation of the inducer. All the methods included in this study have been previously used to measure simultaneous color contrast, but each has limitations. There is no truly independent comparison patch with which to make an asymmetric match. A comparison patch in a black surround is free-floating and will tend to appear achromatic when it is desaturated. When the comparison surround is black, there is also the potential problem that each observer may judge the chromaticity of a free-floating patch in relation to his or her own achromatic point, which will vary across

observers. When the comparison patch is presented on its own surround, there is simultaneous color contrast between comparison patch and surround that will interfere with absolute measurement of color induction in the test patch. In terms of the constancy theory, a large neutral comparison surround may diminish the amount of induction if the neutral field is interpreted as the chromaticity of the illuminant.

Nulling has the advantage that there is no comparison field, but many observers are unable to find a null, instead reporting that their percept of the test patch flips as it reaches the chromaticity of the surround. Dichoptic matching achieves greater agreement between observers, but viewing is unnatural because the two eyes are maintained in different adaptive states. When the eyes are allowed to maintain different adaptive states, dichoptic matching does not measure simultaneous color contrast, but long-term chromatic adaptation. Dichoptic matching with short durations and where the eye of presentation of the test patch changes, as we used here, may be the most reasonable method of measuring simultaneous color contrast.

Acknowledgement

J. B. held an MRC studentship.

References

- Barbur, J. L., de Cunha, D., Williams, C. B., & Plant, G. (2004). Study of instantaneous color constancy mechanisms in human vision. *Journal of Electronic Imaging*, 13, 15–28.
- Bosten, J. M., & Mollon, J. D. (2010). Is there a general trait of susceptibility to simultaneous contrast? *Vision Research*, 50, 1656–1664.
- Brenner, E., Cornelissen, F., & Nuboer, J. F. W. (1988). Simultaneous colour contrast under various experimental conditions. *Perception*, 17, 378.
- Crane, R. L. (1917). The effect of absolute brightness upon color contrast. *American Journal of Psychology*, 28, 597–607.
- Cunthasaksiri, P., Shinoda, H., & Ikeda, M. (2004). Recognized visual space of illumination: A new account of center-surround simultaneous color contrast. *Color Research & Application*, 29, 255–260.
- De Valois, R. L., Webster, M. A., De Valois, K. K., & Lingelbach, B. (1986). Temporal properties of brightness and color induction. *Vision Research*, 26, 887–897.
- Ekroll, V. (2005). Thesis. *On the nature of simultaneous color contrast*. Christian-Albrechts-Universität zu Kiel.
- Ekroll, V., Faul, F., Niederée, R., & Richter, E. (2002). The natural center of chromaticity space is not always achromatic: A new look at color induction. *Proceedings of the National Academy of Sciences of the United States of America*, 99, 13352–13356.
- Ekroll, V., Faul, F., & Wendt, G. (2011). The strengths of simultaneous color contrast and the gamut expansion effect correlate across observers: Evidence for a common mechanism. *Vision Research*, 51, 311–322.
- Fisher, R. A. (1942). *The design of experiments* (3rd ed.). London: Oliver and Boyd Ltd.
- Hambrouck, M. (1975). Etude psychophysique des contrastes chromatiques simultanés. *Vision Research*, 15, 9–21.
- Helmholtz, H. L. F. von. (1909). *Treatise on physiological optics, Sections 23 and 24*. Translation (1924) by Southall, J. P. C. (Ed.). Reprinted. New York: Dover, 1962.
- Jaensch, E. (1919). Ueber Grundfragen der Farbenpsychologie. *Zeitschrift für Sinnesphysiologie*, 83, 257–265.
- Kingdom, F. (1997). Simultaneous contrast: the legacies of Hering and Helmholtz. *Perception*, 26, 673–677.
- Kinney, J. (1962). Factors affecting induced color. *Vision Research*, 2, 503–525.
- Kirschmann, A. (1891). Ueber die quantitativen Verhältnisse des simultanen Helligkeits- und Farben-Contrastes. *Philosophische Studien*, 6, 417–491.
- Köhler, J. (1904). Der simultane Farben- und Helligkeitskontrast, mit besonderer Berücksichtigung des sog. Florkontrastes. *Archiv für die gesamte Psychologie*, 2, 423–524.
- Krauskopf, J., & Gegenfurtner, K. (1992). Color discrimination and adaptation. *Vision Research*, 32, 2165–2175.
- Krauskopf, J., Zaidi, Q., & Mandler, M. B. (1986). Mechanisms of simultaneous color induction. *Journal of the Optical Society of America. A, Optics and Image Science*, 3, 1752–1757.
- Land, E. H., & Daw, N. W. (1962). Colors seen in a flash of light. *Proceedings of the National Academy of Science of the USA*, 48, 1000–1008.
- Lotto, R. B., & Purves, D. (2000). An empirical explanation of color contrast. *Proceedings of the National Academy of Sciences of the USA*, 97, 12834–12839.
- MacLeod, D. I. A., & Boynton, R. M. (1979). Chromaticity diagram showing cone excitation by stimuli of equal luminance. *Journal of the Optical Society of America*, 69, 1183–1186.
- Mollon, J. (2006). Monge: the Verriest lecture, Lyon, July 2005. *Visual Neuroscience*, 23, 297–309.
- Monge, G. (1789). Mémoire sur quelques phénomènes de la vision. *Annales de Chimie*, 3, 131–147.
- Ovenston, C. A., & Whittle, P. (1996). Improved discrimination near the background field: transfer of the “crispning effect” to colour. *Perception*, 25 (Suppl. 16).
- Polden, P. G., & Mollon, J. D. (1980). Reversed effect of adapting stimuli on visual sensitivity. *Proceedings of the Royal Society of London, Series B*, 210, 235–272.
- Shepherd, A. J. (1999). Remodelling colour contrast: Implications for visual processing and colour representation. *Vision Research*, 39, 1329–1345.
- Valberg, A. (1974). Color induction: Dependence on luminance, purity, and dominant or complementary wavelength of inducing stimuli. *Journal of the Optical Society of America*, 64, 1531–1540.
- von Kries, J. (1878). Beitrag zur Physiologie der Gesichtsempfindungen. *Archiv für Anatomie und Physiologie*, 2, 505–524.
- von Kries, J. (1970). Contribution to the physiology of visual sensations. In D. MacAdam (Ed.), *Sources of color science*. Cambridge, MA: MIT Press.
- Washburn, M. (1904). Review of “Der simultane Farben- und Helligkeitskontrast, mit besonderer Berücksichtigung des sog. Florkontrastes”. *Psychological Bulletin*, 1, 368–370.
- Whittle, Paul. (1992). Brightness, discriminability and the “crispning effect”. *Vision Research*, 32, 1493–1507.
- Whittle, P. (1994a). The psychophysics of contrast brightness. In A. Gilchrist (Ed.), *Lightness, brightness and transparency*. Hillsdale, New Jersey: Lawrence Erlbaum Associates.
- Whittle, P. (1994b). Contrast brightness and ordinary seeing. In A. Gilchrist (Ed.), *Lightness, brightness and transparency*. Hillsdale, New Jersey: Lawrence Erlbaum Associates.
- Whittle, P. (2003). Contrast colours. In R. Mausfeld & D. Heyer (Eds.), *Colour perception: Mind and the physical world*. Oxford: Oxford University Press.
- Wichmann, F. A., & Hill, N. J. (2001a). The psychometric function: I. Fitting, sampling, and goodness of fit. *Perception & Psychophysics*, 63, 1293–1313.
- Wichmann, F. A., & Hill, N. J. (2001b). The psychometric function: II. Bootstrap-based confidence intervals and sampling. *Perception & Psychophysics*, 63, 1314–1329.
- Wyszecki, G., & Stiles, W. S. (1982). *Color science. Concepts and methods, quantitative data and formulae*. New York: John Wiley and Sons.