

# STUDIES ON COLOUR CONSTANCY IN MAN

## USING A "CHECKERBOARD - MONDRIAN"

Annette Werner

Institut für Neurobiologie  
Freie Universität Berlin  
Königin-Luise-Str. 28-30  
D-1000 Berlin 33

### INTRODUCTION

Colour constancy is referred to as the ability of colour vision systems to code object colours so that they are perceived approximately constant despite changes in illumination. This phenomenon has been observed in both vertebrates e.g. man (Land, 1977) and invertebrates e.g. the honeybee (Werner et al., 1988), and is of general importance for investigations on colour coding. Chromatic interactions between different visual field areas were found to be a significant feature of information processing underlying colour constancy in both species.

Local border contrasts are thought to be an essential part of spatial integration (Land, 1977; Shapley, 1986), and for this reason it would be interesting to know how closely colour constancy is related to local contrasts. The failure of colour constancy i.e. the actual invariance of the contrast signals, is also discussed.

### METHODS AND EXPERIMENTAL PROCEDURE

Colour constancy in man was investigated by means of a "Checkerboard-Mondrian", in which 13 differently coloured glass plates were mounted in a vertical plexiglass frame with black areas acting as separators (Fig. 1). Each unit square subtended  $2 \times 2$  degree visual angle. The apparatus was shielded from daylight and homogeneously illuminated from behind by a mixture of 3 different lamps of short-, middle- and long-wavelength (S, M, and L respectively); the chosen wavelengths corresponding to the 3 spectral types of human cones i.e.  $\lambda_{max} = 430 \text{ nm}$ ,  $540 \text{ nm}$ ,  $660 \text{ nm}$ . The wavelength-band intensity of each lamp could be varied individually. Spectral distribution of the emitted light was measured for each of the 13 colour squares and colour stimuli were quantitatively determined by calculating the related tristimulus values X, Y, and Z, that correspond to the relative amount of light absorbed in the 3 types of cones. Test subjects viewed the Mondrian against a black background.

Five colour constancy experiments with different reference colours and different illumination changes are described; the number of test persons per test is 10. Colour constancy was tested in a forced choice paradigm, candidates marking the position of the supposed reference plate on a black and white diagram.

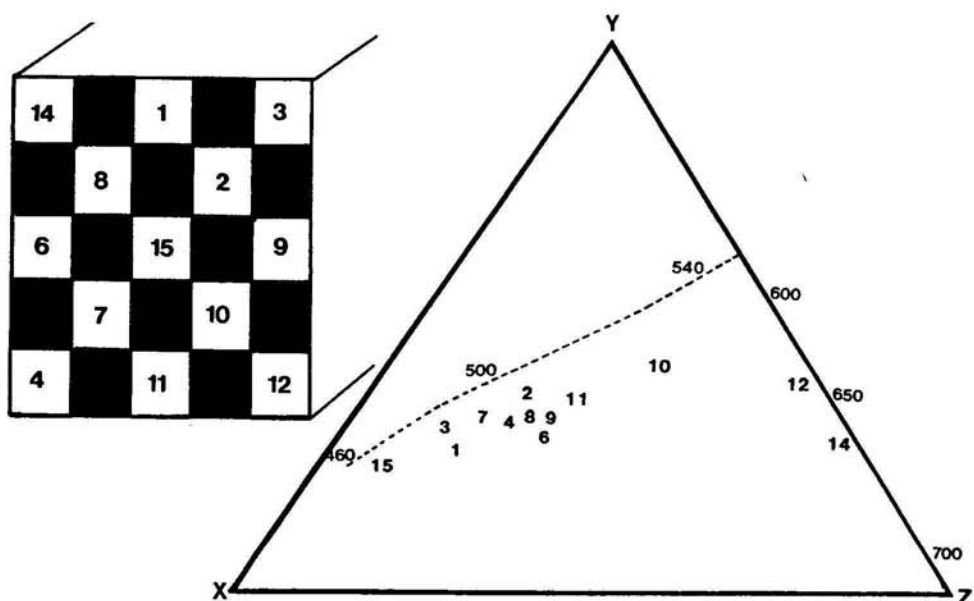


Fig. 1. Schematic drawing of the "Checkerboard-Mondrian" and Mondrian stimuli for the standard illumination in a physiological colour triangle. X, Y, and Z, represent the chromaticity values which are related to each stimulus.

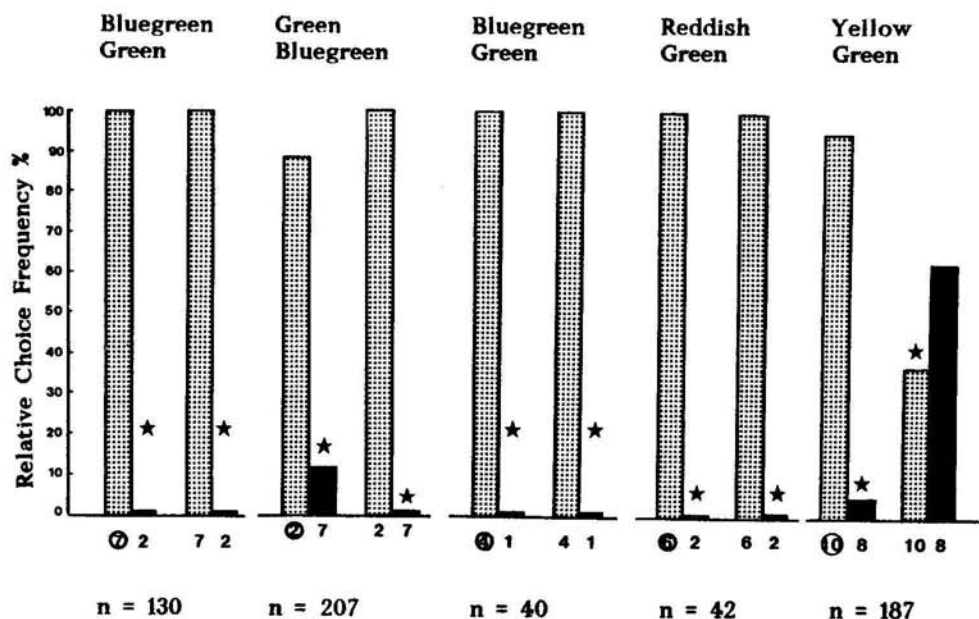


Fig. 2. Performance of colour constancy in different spectral regions and for different illumination changes. Relative choice frequency gives the choice distribution of choices between the reference plate (encircled number) and the matching alternative. n = number of decisions, \* indicates significant differences in choice frequency.

This task was performed both under a standard illumination and then, in further tests, with different colour matching illuminations. For each colour match, the illumination of the whole Mondrian was changed in such a way that only one of the alternative plates (the so-called "matched alternative") now emitted exactly the same light flux (i.e. resulting in the same tristimulus values) as the reference plate emitted previously during the standard illumination conditions. This colour match was performed 10 times for each test subject, and the position of the plates within the Mondrian altered for each test. Results are given as the distribution of decisions made for the reference plate and the matching alternative (rel. choice frequency % - see Fig. 2). Colour constancy was determined by comparing the choice behaviour in the discrimination and colour constancy tests. In the case of perfect colour constancy, one would expect the distribution of choice behaviour between the training and the alternative matching plate to remain the same. Alternatively, if normalization of receptor signals does not occur, perception would be determined by the absolute spectral light fluxes of the plates. Therefore, under the changed illumination one would then expect the matched alternative plate to be chosen with the same frequency as the training plate during the discrimination test.

## RESULTS

### 1. Coding Contrasts

Contrasts are an appropriate code to carry constant information under conditions of varying illumination as they represent the relationships between reflections of different surfaces. However, this is only true for situations where surface reflections change accordingly i.e. illumination changes act simultaneously and similarly on all surfaces (as is the case in Land's Mondrian). In the checkerboard arrangement presented here, the black separators between the colour plates ensure that border contrasts between the equally illuminated colour fields are limited to the corners of each plate. In other words, if the illumination is varied, the majority of local contrast signals do not remain constant since illumination changes affect the colour plates only (as opposed to the black fields). If colour constancy is primarily based on short range interactions then no colour constancy would be expected under the checkerboard condition.

Colour constancy was tested for 5 different colour matches in different spectral regions. In Fig. 2, the first double block ("train.") of every experiment shows the distribution of choices between the test plate and alternative plate during standard illumination conditions and the second double block ("match.") shows the distribution of choices during the changed illumination. The choice behaviour of the observers does not change in 4 of the 5 colour matches, and this indicates that there is a compensation in the physical colorimetric shift. The lack of constant border contrasts is, therefore, not a limiting factor for colour constancy - at least under the given experimental conditions. In experiment 10/8 colour constancy is not observed and this indicates that the experimental procedure is sensitive enough to detect for situations where the colour vision system cannot cope with illumination changes.

### II. A possible reason for the failure of colour constancy

The effects of illumination changes on receptor signals were determined for experiment 10/8 (failure of constancy) and experiment 2/7 (successful compensation for illumination change). In order to detect differences which can be traced back to the coding of these signals in relation to their surround, i.e. contrast coding, a simple spatial normalization procedure is applied for calculating the receptor signals (Fig. 3a). This computation can be described as the weighting of each signal by the chromatic average of all the colour signals of the surrounding background, and separately for each chromatic channel. It is, therefore, comparable to a von Kries transformation (von Kries, 1905). Receptor signals are derived from

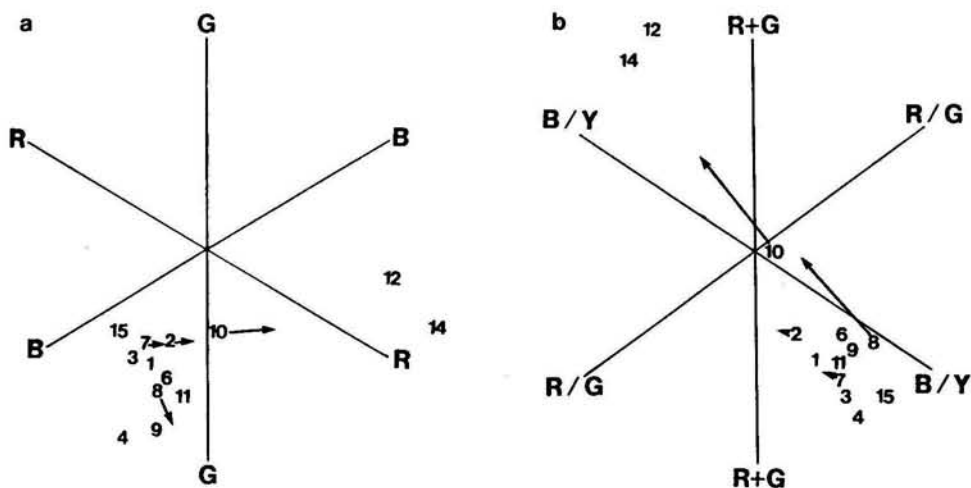


Fig. 3a. Effect of illumination change on the level of receptor signals after normalization. Colour loci are presented in a 2-dim. projection of a vector space whose axes represent the quantities of receptor signals R, G, B. Arrows indicate the occurring shifts of the colour loci of Nos: 2 and 7 in experiment 2/7, and Nos: 10 and 8 in experiment 10/8.  $\Delta$  gives the Euclidian distance between the loci of the reference and alternative matching plate under matching illumination, and the locus of the reference stimulus under standard illumination respectively:  $\Delta$  (2-2) = 1.17;  $\Delta$  (2-7) = 0.62;  $\Delta$  (10-10) = 1.26;  $\Delta$  (10-8) = 7.4.

Fig. 3b. Effect of illumination changes on the level of opponent signals after normalization. The diagram represents a 2 dim. projection of a vector space whose axis are given by the normalized spectral opponent signals R/G, B/Y and R+G.  $\Delta$  (2-2) = 1.22;  $\Delta$  (2-7) = 2.21;  $\Delta$  (10-10) = 6.48;  $\Delta$  (10-8) = 5.7.

the cone absorption values i.e. tristimulus values by a logarithmic transformation. In Fig. 3a the loci under standard illumination are indicated by the numbers of the colour plates 2, 7, 10, and 8, and arrowheads give the position of the loci of the same plates under the matching illuminations. As can be seen by the distances  $\Delta$  between the reference loci under standard illumination and the colour loci under matching illumination, the normalization procedure predicts that plate No: 7 should be mistaken for plate No: 2, whereas plate No: 10 should be well discriminated from No: 8. This is in contradiction to the experimental results shown in Fig. 2.

The same normalization procedure was applied to the opponent signals, which were calculated as a linear combination of the weighted receptor signals (see Fig. 3b). Weighting factors were taken from Guth et al. (Guth, 1980). It should be mentioned that in contrast to Worthy's calculations (Worthy, 1985) the normalization process is applied directly to the opponent signals. Normalization of the opponent signals predicts that plate No: 2 should be recognized as the reference plate, whereas in experiment 10/8 plate No: 8 should be mistaken for plate No: 10 (see loci differences  $\Delta$ ), and Fig. 2 shows that this is indeed the case. Therefore, the observed lack of colour constancy in experiment 10/8 can be interpreted as a normalization of opponent signals.

## DISCUSSION

Since local contrasts in the "Checkerboard-Mondrian" do not provide a constant cue for coding colour signals under varying illumination conditions, the observed colour constancy cannot be directly related to local contrasts. Additional long-range interactions, as demonstrated by Gelb (1929), Land et al. (1983) and Pöppel (1986), contribute to spatial integration, and this is particularly so if the intermediating area is black (Valberg et al., 1985; see also this volume). However, the integration of long-range contrast signals cannot lead to colour constancy immediately since the colour plates contribute to only 50% of the total Mondrian area (independent of which radius around the chosen reference field is taken for the integrating area). I assume, therefore, that colour constancy is derived by repeated steps of contrast integration, where local contrasts are the initial input stage. This assumption takes into account the simultaneous effect of long-range interactions and the role of distance-weighted local contrasts. Indeed, algorithms such as Blake's modified Horn's Algorithm, which involve iterative differentiation of contrast signals, can successfully be applied "for recovering reflectance in the Mondrian world" (Blake, 1985). However, it should be mentioned that the complete failure of constant local contrasts may affect the performance of colour constancy (Walraven et al., 1990).

Quantification of the effect of a spatial normalization of receptor and spectral opponent signals suggests that colour constancy is not appropriately described at the level of receptor signals, but is rather the result of continuous steps of contrast integration in the on-going processing of chromatic information between the retina and the areas of the visual cortex.

## REFERENCES

- Blake, A., 1985, On lightness computation in the Mondrian world, in: "Central and Peripheral Mechanisms of Colour Vision", T. Ottoson and S. Zeki, ed., MacMillan, New York.
- Gelb, A., 1929, Die Farbkonstanz der Sehdinge, in: "Handbuch der normalen und pathologischen Physiologie", Vol. 12, A. Bethe, G. V. Bergmann, G. Embden and A. Ellinger, ed., Springer, Berlin.
- Guth, S. L., Massof, R. W., and Benzschawel, T., 1980, Vector model for normal and dichromatic colour vision, *J. opt. Soc. Am.*, 70(2):197.
- Kries, J. v., 1905, Die Gesichtsempfindungen, in: "Handbuch der Physiologie des Menschen", Vol. 3, W. Nagell, ed., Vieweg, Braunschweig.
- Land, E. H., 1977, The retinex theory of colour vision, *Sci. Am.*, 108.
- Land, E. H., Hubel, D. H., Livingstone, M. S., Perry, S. H., and Burns, M. M., 1983, Colour generating interactions across the corpus callosum, *Nature*, 303:616.
- Pöppel, E., 1986, Longrange colour generating interactions across the retina, *Nature*, 320(10):523.
- Shapley, R., 1986, The importance of contrast for the activity of single neurons, the VEP and perception, *Vision Res.*, 26(1):45.
- Valberg, A., Lee, B. B., Tigwell, D. A., and Creutzfeldt, O. D., 1985, A simultaneous contrast effect of steady remote surrounds on responses of cells in macaque lateral geniculate nucleus, *Exp. Brain Res.*, 58:604.
- Walraven, J., Enroth-Cugell, C., Hood, D. C., MacLeod, D. I. A., and Schnapf, J. L., 1990, The control of visual sensitivity: Receptor and postreceptor processes, in: "Visual Perception: The Neurophysiological Foundations", L. Spillmann and J. S. Werner, ed., Academic Press, San Diego.
- Werner, A., Menzel, R. and Wehrhahn, Chr., 1988, Colour constancy in the honeybee. *J. Neurosci.* 8:156.
- Worthy, J. A., 1985, Limitations of colour constancy, *J. opt. Sci. Am. A*, 2(7):1014.