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Second-order statistics of colour codes modulate transformations that effectuate varying degrees of scene invariance and illumination invariance

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Abstract. We argue, from an ethology-inspired perspective, that the internal concepts 'surface colours' and 'illumination colours' are part of the data format of two different representational primitives. Thus, the internal concept of 'colour' is not a unitary one but rather refers to two different types of 'data structure', each with its own proprietary types of parameters and relations. The relation of these representational structures is modulated by a class of parameterised transformations whose effects are mirrored in the idealised computational achievements of illumination invariance of colour codes, on the one hand, and scene invariance, on the other hand. Because the same characteristics of a light array reaching the eye can be physically produced in many different ways, the visual system, then, has to make an 'inference' whether a chromatic deviation of the space-averaged colour codes from the neutral point is due to a 'non-normal', ie chromatic, illumination or due to an imbalanced spectral reflectance composition. We provide evidence that the visual system uses second-order statistics of chromatic codes of a *single* view of a scene in order to modulate corresponding transformations. In our experiments we used centre – surround configurations with inhomogeneous surrounds given by a random structure of overlapping circles, referred to as Seurat configurations. Each family of surrounds has a fixed space-average of colour codes, but differs with respect to the covariance matrix of colour codes of pixels that defines the chromatic variance along some chromatic axis and the covariance between luminance and chromatic channels. We found that dominant wavelengths of red – green equilibrium settings of the infield exhibited a stable and strong dependence on the chromatic variance of the surround. High variances resulted in a tendency towards 'scene invariance', low variances in a tendency towards 'illumination invariance' of the infield.

1 The problem of the structural format of perceptual representations

Colour perception has long been regarded as a kind of integrated domain of its own that can be studied in isolation from other perceptual attributes. Though such a view has proven highly fruitful for the neurophysiological purposes of understanding various stages of neural colour coding, it has been at a considerable cost to perceptual psychology, of which Helmholtz and Hering were already well aware. They realised that concepts from sensory physiology alone do not constitute an appropriately rich theoretical language for dealing with perception but that a richer set of concepts, including "unconscious inferences" in the case of Helmholtz, is required for appropriate explanatory frameworks. Since then, many writers, notably in the tradition of Gestalt psychology and ethology, have emphasised that a successful explanatory account of perception has to be based on an appropriately rich set of internal primitives, which specify the internal data format, as it were. Though available theoretical and empirical evidence strongly suggests that primitives such as 'surface', 'object', or 'event' (understood as *internal* concepts) are among the pillars on which the structure of perceptual representations rests, we are still far from having a clear theoretical picture about the kind of primitives underlying perceptual representations. Perceptual psychology has predominantly focused on *processes* of information flow and paid little attention to explicitly addressing the problem of the *structural format* within which the internal coding processes take place or to identifying the primitives on which complex perceptual representations are built. A similar diagnosis holds for cognitive psychology in general, where, "one typically finds rather perfunctory discussion of information structure only as a prelude or postlude to extensive treatment of processing" (Jackendoff 1987). An essential task of perceptual psychology thus continues to be the identification of the primitives of the internal conceptual structure of perception, of their 'data structure' and of their associated types of transformations that operate on these primitives.

For this purpose, it is important not to confuse the physical concepts underlying a particular generation process that causes the structure of a sensory input with the internal concepts underlying a parsing of the incoming light array in terms of internal codes. The only information that the visual system has at its disposal is the physico-geometrical information contained in the incoming light array. The interesting question then is how the structural properties of the incoming light array are exploited by the visual system in terms of its primitives. The problem of identifying the conceptual structure of perception would be trivialised by lumping together concepts of perceptual and physical categories and by 'explaining' the former as a computational recovery of the latter (cf Mausfeld 2002a). Perceptual and physical categories do not coincide. For instance, the existence of physical objects is not only not sufficient but not even necessary for the corresponding percept (think of an object on a CRT screen or in a virtual reality setting).

2 Basic aspects of the structural form of colour coding

In colour perception, a locally atomistic research perspective has long impeded an appropriate understanding of the internal structural form of colour coding. According to this conception, there are some kinds of 'raw colours' that are given by the receptor excitations elicited by the local incoming light stimulus and that are transformed in subsequent stages of processing in order to fulfil certain requirements, such as sensitivity regulations, optimal and efficient coding, or invariance requirements. Representations of, say, surface colours are regarded as being built up from transformations of primary colour codes by 'secondary' and 'higher' processes. Many classic writers have pointed out the inadequacy of such conceptions (eg Kardos 1934; MacLeod 1947). Koffka (1932, pp 337 f.), following Gelb (1929/1938), considered the distinction between "transformed and untransformed colour", whereby "transformation means a special new process which modifies the peripherally excited processes" as "entirely unjustified". Gelb considered the distinction between 'physiological' and 'psychological' levels as "wrong" and regarded, in Gelb (1932), any such "dualisms of explanatory principles" as inappropriate and misleading.

In colour research, but interestingly not in research on brightness perception, the insights, frequently expressed in the classic literature, that the structure of internal colour coding cannot be understood by conceiving of colour as an isolated attribute and that "a general theory of colour must at the same time be a general theory of space and form" (Koffka 1936, p. 129) have sunk into oblivion. This situation, however, has improved during the last years. There is once again a wakening interest, still predominantly in the lightness literature, in experiments and observations that try to explore the idea that colour representations intrinsically depend on "modes of organisation" (eg Gilchrist et al 1999; Schirillo and Shevell 2000), and thus in what Katz (1930) aptly called the "marriage of colour and space". From our theoretical perspective (cf Mausfeld 2002b), we prefer to speak, instead of 'modes of organisation', of the interdependences in the data structure of representational primitives, where free parameters referring to colour, depth, orientation, etc interact in complex ways, which are still poorly understood. These interdependences contribute to the fact that internal concepts, such as 'surface colour', defy definition in terms of a corresponding physical concept (even in the sense of the latter providing necessary and sufficient conditions for the former); rather they have their own peculiar and yet-to-be identified relation to the sensory input and depend intrinsically, in a way that cannot simply be derived from considerations of external regularities, on other *internal* codes (such as internal codes for perceived depth or figural organisation). This relation determines the 'inner semantics', as it were, of the representational primitives, which extensionally can be understood as the equivalence classes of physical situations by which they are triggered. Whatever the exact nature of this relation turns out to be, the structure of representational primitives will be shaped by specific invariance requirements that (partly) mirror adaptively significant regularities in the external environment. In the present context, invariance requirements pertaining to the (idealised) computational goals of scene invariance, ie invariance of local colour codes under changes of scene composition, and of illumination invariance stand out as being of fundamental importance (cf Brown 2002).

3 Scene invariance versus illumination invariance

The problem of illumination invariance has attracted much more attention than the problem of scene invariance in the history of colour science (cf Gilchrist 1994, pages 21–22). Under the heading of 'colour constancy', illumination invariance came to be regarded as a problem confined to 'pure' colour perception, where transformations of some 'raw' or primary colours result in a discounting of the illuminant. Particularly within the so-called adaptational approaches, which originated in the work of Ives (1912) and Jaensch (1921) and extend to modern von Kries-type and ratio-based coding schemes, the problem of colour constancy, by idealising away the perception of the illumination, became misidealised and misrepresented. This was clearly recognised in the early literature in the field. Gelb (1929, p. 610/1938) acknowledged David Katz for being "the first to really recognise that colour constancy cannot be understood within the abstractly isolated domain of colour as such but only within comprehensive investigations into the structure of our spatially articulated perceptual world". The nature of the problem involved was, however, first discerned by Gelb himself. On the basis of the theoretical and empirical evidence available at that time, he insisted that "the problem of colour constancy, rather than being a problem of an alleged discrepancy between 'stimulus' and 'perceived colour', has to do with the general problem of the constitution and structure of our perceptual visual world. The phenomenal segregation into illumination and illuminated object (ie the correlate of the percept 'object colour') reveals a propensity of our sensorium and is nothing but the expression of a certain structural form of our perceptual visual world" (Gelb 1929, p. 672/1938)

While, within a locally atomistic perspective, phenomena related to colour constancy appear to be in greater need of explanation, the complementary problem of scene invariance did not require, within this perspective, any explanation at all. Scene invariance can, in an idealised way, be understood as the functional requirement that the colour designators of a location in a scene should be independent of the colour designators of the neighbouring locations. Its importance can only be appreciated once the locally atomistic perspective has been overcome. The question that has to be dealt with is: On the basis of which information can the visual system decide whether, and to what extent, to differentially activate mechanisms subserving (presumed) computational goals of scene invariance and of illumination invariance? From our theoretical perspective we like to conceive of this differential activation in terms of a parameterised family of transformations, whose parameters are determined by some internal representation of the illumination. [An example of this type of transformational structure can be found in the Maloney's (1992) algorithm, where the location of the best-fitting plane in tristimulus space determines the transformation from three-dimensional stimulus codes to two-dimensional surface colour codes.] The question at issue then is which physico-geometrical properties of the sensory input determine these parameters.

The same characteristics of a light array reaching the eye can be physically produced in many different ways (eg by a certain interaction of physical surfaces and light sources or, with the use of a slide or a CRT screen, by light sources alone). The visual system cannot distinguish these cases: it simply doesn't know whether the causal chain giving rise to this pattern arises from surfaces and light, or lights alone. We thus encounter two different levels of analysis. One level of analysis pertains to questions of how relevant properties of the external world are mirrored in the properties of the incoming light array and thus to the study of where these properties 'normally' stem from in our environment. On this level, which can be considered as part of ecological physics, important insights have been achieved more recently (eg Maloney 1992; Ruderman et al 1998). The second level of analysis investigates how structural properties of the incoming light array are exploited by the visual system in terms of its primitives. Such investigations heuristically draw on many sources, such as phenomenological observations, experimental observations on the dependence of colour appearance on perceptual organisation, or considerations from ecological physics. The experiments on the role of second-order statistics of colour codes in a scene that we report in this paper are based on heuristics referring both to phenomenological observations as well as to physical considerations concerning the interplay of surfaces and illuminants with respect to colour.

4 The role of second-order statistics for the modulation of transformations that effectuate varying degrees of scene invariance and illumination invariance

Phenomenological observations on the interplay of surfaces and illumination provide a rich source for theoretical conjectures about the internal structure of colour representation. There are many phenomenal peculiarities that are characteristic for colour appearances under (chromatic) illumination. Many of these have not received due attention—neither within an elementaristic perspective nor within functionalist-computational approaches. Among the peculiarities that appear to us of great theoretical significance in the present context—though we will not elaborate upon them here—are "the curious lability of colours under chromatic illumination" (Katz 1911, p. 274), phenomena of what Helmholtz called seeing two colours "*at the same location* of the visual field one behind the other", and what Bühler (1922) called "locating colours in perceptual space one behind the other", and observations that, for instance, in the case of a red surface viewed under a reddish illumination, the "red and colours in its vicinity are not simply perceived as red, but rather appear in a strange way brightened, glimmering and above all somehow whitened" (Bocksch 1927).

We will limit ourselves to the very simple phenomenological observation that, say, in a room that contains objects and surfaces of a great variety of different colours, the gamut of colour appearances tends to shrink with increasing deviation of the illumination from a white one. This phenomenal observation of a shrinkage in the gamut corresponds to, but cannot be identified with, physical observations on the interplay of illumination spectral energy distributions and surface spectral reflectances. This physical interplay was mathematically investigated by Schrödinger (1920) with the use of idealised "optimal colour" reflectances. In terms of his analysis, the volume of the "optimal colour solid", ie the points in tristimulus space that belong to all possible "optimal colour" reflectances under a given illumination, decreases with decreasing bandwidth of the illumination, whereas white broadband lights yield large volumes. Hence information about this volume might provide valuable information about the presence and kind of a chromatic illumination.

Forsyth (1990) proposes, for a Mondrian world, a computational procedure for extracting illuminant information hidden in the gamut of Grassmann codes of the surface reflectances under some illuminant. For the idealised situation of the presence of all possible reflectances, Andres (1997) has shown that it is possible to reconstruct the spectral distribution of the illuminant, or, in other words, that the shape of the optimal colour solid under a given illuminant characterises this illuminant completely.

In a real scene, optimal reflectances are not present, however. Yet, in these situations the shape and the volume of the gamut of the Grassmann codes should also provide a clue to the illuminant. So the question arises: Which scene statistics might yield at least some valuable information about form and shape of this gamut? The first-order and second-order statistics of the scatter of colour codes in a scene may, in fact, roughly describe important features: the mean (first order) gives the centre of the gamut, whereas the covariance matrix (second order) contains important information about volume and shape because it allows variances and correlations of all linear combinations of colour codes linearly related to the Grassmann codes to be obtained.

On the basis of a corresponding physical regularity, the visual system could employ—by inverting, as it were, this physical observation—the heuristics that a low 'variance' of colour codes in a scene is, other things being equal, a cue for the presence of an illumination that deviates in a characteristic way from a white one. The 'variance', or, more precisely, the covariance structure, is a promising candidate for the abovementioned modulation parameter.

Thus, physical analyses as well as phenomenological observations suggest that the '*variance of colour codes*', or, more precisely, the covariance matrix of the distribution of colour codes, in the incoming light array is a reliable regularity on which an 'inference' can be based about whether a chromatic deviation of the space-averaged colour codes from the neutral point is due to a 'non-normal', ie chromatic, illumination or due to an imbalanced spectral reflectance composition.

5 Seurat stimulus configurations as 'minimal' scenes for investigating effects of scene statistics of chromatic codes

We employ, along the line of previous papers (Mausfeld and Niederée 1993; Mausfeld 1998), centre–surround stimuli as a kind of 'minimal' stimuli that, owing to their specific figural organisation, suffice to trigger mechanisms that, under 'normal' viewing conditions, subserve functional goals related to the interplay of surfaces and illuminations. Because we are interested in the differential activation of mechanisms pertaining to scene invariance and illumination invariance, as well as in potential transitions between these, we modify the surround so that it contains a kind of spatial microstructure. The advantages of this are twofold: it is likely to increase the effectivity of centre–surround configurations with respect to the mechanisms under scrutiny and it also allows theoretically interesting parameters of the surround, understood as the 'visual scene' that the visual system encounters, to be varied systematically. This is consonant with earlier observations by, among others, Katz, Gelb, Kardos, and Burzlaff. For instance, Gelb (1929/1938) emphasised that "the segregation of illumination and illuminated object" requires an "articulation of the visual field" ("reiche Sehfeldgliederung"). Kardos (1929) even conjectured, with respect to configurations of a small patch in an extended surround, that "probably this simple bipartition constitutes the most favourable conditions for a segregation of illumination and illuminated object". Under these conditions, this segregation critically depends on the presence of some microstructure in the visual field, as was repeatedly emphasised in the classic literature (Kardos 1929; Katz 1930; Gelb 1932). For test fields that are surrounded by a chromatically varied surround, Brown and MacLeod (1997) observed a perceptual "gamut expansion" when a comparison was made to test fields with a uniform surround. Since 'articulation', which is a pre-theoretical notion, can refer to quite different features of a scene, we have to decide how to theoretically specify it in terms of input features that are related to specific perceptual representations. Our specification will be in terms of second-order statistics of chromatic codes in the surround.

We constructed a class of centre–surround configurations for which the second-order statistics of the microstructure of the surround can be varied, independently of first-order statistics, in a systematic and controlled way. For each given homogeneous surround (characterised by the corresponding Grassmann coordinates) a family of spatially inhomogeneous surrounds, which have the same space-averaged Grassmann coordinates (globally, and within several smaller annular regions of increasing distance from the infield), is constructed. The geometrical layout of spatial variations of the surround is given by a random structure of overlapping circles (with occluding intersections) of a fixed diameter (defining bandwidth of spatial variation) (see figure 1).

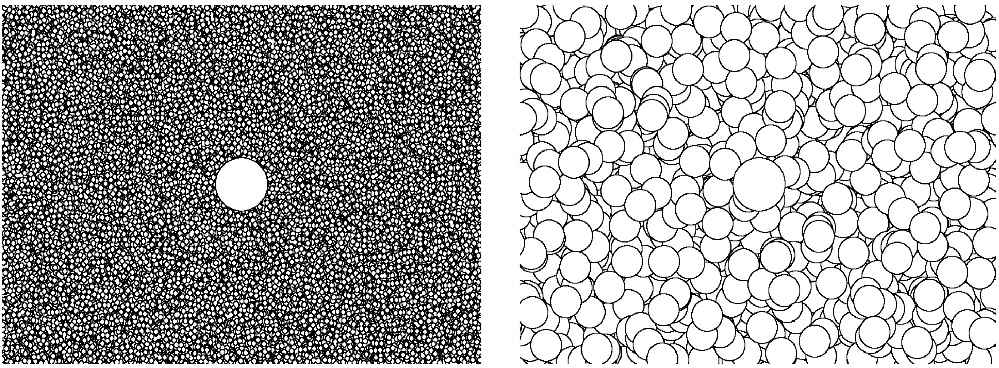


Figure 1. Typical geometrical layout of Seurat configurations.

The microstructure to which the surround configurations perceptually give rise can, particularly for larger circles, also incorporate aspects of a flat 3-D appearance, due to the occlusion cues provided by the overlapping circles. The infield consists of a circular field whose colour is under the control of the observer.

We constructed families of configurations that have a fixed space-average of colour codes (with respect to some coordinate system of colour codes) but differ with respect to the covariance matrix of colour codes of pixels that defines the chromatic variance along some chromatic axis, and the covariance between luminance and chromatic channels. For example, one can independently vary the degree of modulation along the luminance axis and the degree of modulation along some chromatic axis. Furthermore, the bandwidth of the microstructure of the surround can be changed by varying the diameter of the circles that make up the surround.

For very small diameters of the circles in the surround, and if both luminance and chromatic modulations are employed, the stimulus configuration is reminiscent of the neo-impressionistic style of painting. Because of this, we refer to our stimuli as Seurat configurations. (A colour reproduction of various types of Seurat configuration can be found in Mausfeld 1998.) Increasing the diameter leads to patterns that resemble, say, a piece of fruit against a background of leaves, or a flower against a background of grass or soil. For circles with very large diameters a Mondrian-type of configuration is obtained. Using these kinds of stimulus configurations, we can systematically investigate continuous transitions of complexity between centre–surround type stimuli with a homogeneous surround and Mondrian-type configurations (and thus different kinds and degrees of articulation).

It is even possible to follow continuous paths between two types of configurations, eg between a degenerate situation in which only luminance varies and chromaticity is constant and another degenerate situation in which luminance is constant and chromaticity varies. The following experiments use some Seurat configurations on such paths, here connecting the degenerate cases of pure luminance variation and of pure chromaticity variation in only one direction. A detailed description of the algorithm used for the construction of Seurat configurations is given in Andres (1997); for a short summary see the appendix.

6 Experiment

6.1 *Seurat configurations used*

We employed, in the experiments reported here, Seurat configurations whose surround was chromatically varied along a red–green axis only (isoluminance condition), along the luminance axis only (isochromatic condition), and along both axes, while the space-average was kept fixed (globally and within 6 smaller annular regions of roughly exponentially increasing distance from the infield). More specifically: in the Seurat configurations used here the xy-chromaticities all lay on the line $y = -0.763x + 0.798$ near the border of the monitor gamut. Thus, all colours were almost as saturated as possible. For convenience this line will be referred to as the red–green axis.

The surrounds were given by a random structure of 1000 overlapping circles, each subtending a visual angle of about 1.0 deg, and subtended a visual angle of 16.1 deg in width and 12.5 deg in height. The size of the infield was 2.0 deg. For reddish surrounds, space-averaged chromaticities of the surround were $(x, y) = (0.515, 0.406)$ with a dominant wavelength of 589 nm. Luminances of the surround were $L = 10.2$ cd m^{-2}. Luminances of the infield ranged between 10.9 and 15.9 cd m^{-2} (increments), and 2.2 and 8.9 cd m^{-2} (decrements).

The construction of the colours of the configurations is based on the prescribed covariance matrix of colour codes. This covariance matrix is geometrically characterised by its eigenvectors and eigenvalues, which determine the shape of the ellipsoid describing the scatter of colour codes: the eigenvectors yield the axes of the ellipsoid, whereas the square roots of the eigenvalues give the radii in the directions of these axes. Therefore the covariance matrices are given here in terms of their eigenvectors and eigenvalues. The first two eigenvectors always lie in the plane E spanned by the vector $\boldsymbol{s}$, representing the average of the surround, and the vector $\boldsymbol{d}$, connecting a green and a red point of equal luminances on the red–green axis. More specifically these vectors are (normalised) $\boldsymbol{s} = (0.780, 0.614, 0.119)'$ and $\boldsymbol{d} = (0.999, 0, -0.044)'$ [all numbers refer to CIE (X, Y, Z) coordinates, unless otherwise indicated].

Now, there are two types of construction: in the case of pure luminance variation, the first eigenvector must have the direction of $\boldsymbol{s}$, in the case of pure chromatic variation, the first eigenvector must have the direction of $\boldsymbol{d}$. In both cases the second eigenvector is chosen perpendicular to the first. These two constructions are referred to as type I and type II. The cases of both luminance and chromatic variation usually follow type I (luminance variation with added chromatic variation). Only one of them follows type II (chromatic variation with added luminance variation). The third eigenvector is perpendicular to the first two with an eigenvalue of approximately 0, so that the colours of all surrounds lie in the plane E (up to deviations caused by the discrete monitor colours).

Consequently, the construction of the surrounds with luminance variation and chromatic variation starts—in the case of type I—with a pure luminance variation, the corresponding eigenvector of which has to be $\boldsymbol{s}$. Then chromatic variation is added in the direction perpendicular to $\boldsymbol{s}$ in CIE colour space. When the eigenvalue corresponding to ***s*** remains the same in several configurations, these are said to belong to different levels of chromatic variation in one level of luminance variation. This terminology refers to the rationale of construction in CIE space, especially to the constant first eigenvalue in ***s*** direction, and does not imply that the variances of the luminance are the same. Although the notion of luminance level may be misleading when interpreted as constant variance, it is retained here for simplicity. The same remark applies to the notion of level of chromaticity variation, which again is defined in terms of the second eigenvalue and not in terms of the variance of chromaticity. The mixed configuration, constructed in a similar way by departing from pure chromatic variation, is classified in the general scheme at an appropriate place.

Table 1 gives the parameters of the construction for the surrounds used in the experiment and some additional descriptive information.

Table 1. Classification of the surrounds used in the experiment and parameters of their construction. The Seurat configuration types are specified in columns 2 and 3 (see text for detailed explanation). The first column provides corresponding labels for reference, L and C indicating levels of luminance and chromatic variation, respectively. By sx and sL we denote the standard deviation, by x_{min}, x_{max}, L_{min}, L_{max} the minimal and maximal values of x- and L-coordinates.

Condition	Type of construction (first eigenvector)	First two eigenvalues	sx	$x_{min} : x_{max}$	sL	$L_{min} : L_{max}$
L : 0, C : 0	Type II (***d***)	0.001; 0.001	0.000	0.515 : 0.515	0.000	10.181 : 10.181
L : 0, C : 1	Type II (***d***)	0.397; 0.001	0.013	0.487 : 0.538	0.034	10.114 : 10.256
L : 0, C : 2	Type II (***d***)	1.217; 0.001	0.022	0.465 : 0.556	0.033	10.107 : 10.256
L : 0, C : 3	Type II (***d***)	3.048; 0.001	0.035	0.432 : 0.575	0.035	10.107 : 10.270
L : 0, C : 4	Type II (***d***)	6.432; 0.001	0.052	0.415 : 0.586	0.034	10.101 : 10.262
L : 1, C : 0	Type I (***s***)	1.226; 0.001	0.001	0.514 : 0.516	0.683	8.816 : 11.484
L : 1, C : 2	Type I (***s***)	1.225; 1.230	0.035	0.451 : 0.581	1.079	7.690 : 12.635
L : 1, C : 3	Type II (***d***)	3.024; 1.223	0.045	0.411 : 0.593	1.073	7.578 : 12.881
L : 2, C : 0	Type I (***s***)	3.022; 0.001	0.001	0.514 : 0.516	1.067	7.970 : 12.265
L : 2, C : 1	Type I (***s***)	3.031; 0.400	0.020	0.479 : 0.560	1.171	7.380 : 12.940
L : 2, C : 2	Type I (***s***)	3.012; 1.227	0.036	0.454 : 0.597	1.352	6.698 : 13.576
L : 2, C : 3	Type I (***s***)	3.045; 3.025	0.056	0.407 : 0.614	1.692	6.741 : 13.955

6.2 *Apparatus*

The stimuli were presented on a MiroC2185 21-inch colour monitor. The monitor was driven by a Pentium PC with a VSG2/3 Cambridge Graphics Board. Monitor calibration was carried out with an IKS X-dap spectroradiometer. Measurements were made at 1024 intervals between 220 nm and 820 nm. The radiance of each of the three phosphors was measured at 17 values, whose relations to the absolute luminance values were determined by calibrating against a Gamma Scientific RS-10A spectral irradiance head.

A viewing box (blackened inside) was placed between the monitor and the observer such that the screen was effectively seen in a completely dark environment. The distance between the screen and the observer was 125 cm. At this viewing distance the visible screen, and thus the surround, subtended a visual angle of 16.1 deg in width and 12.5 deg in height.

In order to achieve stable head position, observers viewed the display with both eyes through suitably modified diver's goggles that were mounted in the front panel of the viewing box and that screened off any other light in their field of view.

Observers used two buttons on a special keyboard for their reddish/greenish judgments. This keyboard also had an additional button that observers pressed to start a new trial and two further buttons for marking configurations that exhibited perceptually interesting features on which they wished to comment.

6.3 *Observers*
Two male observers (27 and 28 years of age) participated in this experiment. Both had normal colour vision and normal acuity. Though both had extensive experience with the judgmental task employed, they were not aware of the purpose of the experiment. Regular spot checks for various parameter conditions were made by one of the authors (RM).

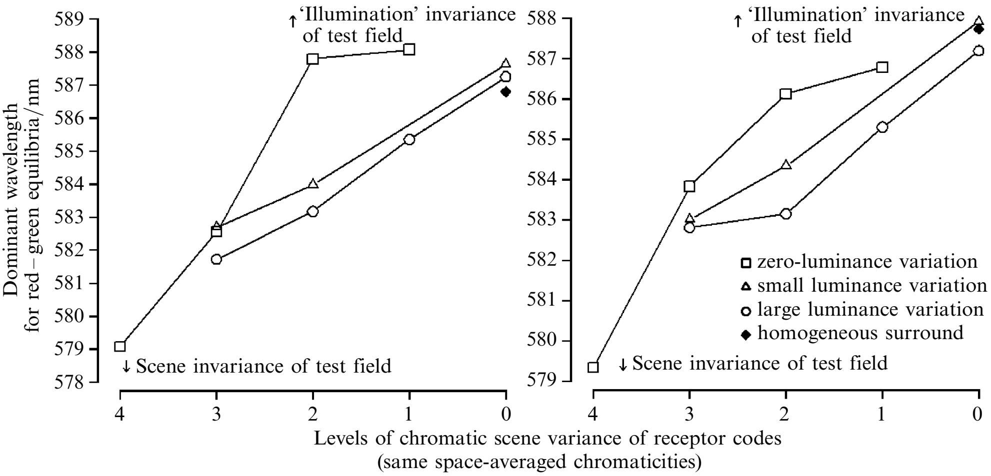
6.4 *Procedure*
The task of the observer was to make reddish/greenish judgments for the infield. Observers were instructed to fixate the infield and to make their judgments at the end of the presentation interval. A forced-choice random double-staircase method was used to determine red – green equilibrium settings. (Note that red – green equilibrium settings function here only as a probe for the propensity of the visual system to activate certain types of transformations with respect to the test spot; no specific assumptions about opponent processing are involved.) During the staircase, the test field was kept at a fixed luminance. The optimal termination parameters for the staircase procedure were determined by a simulation study because initially the mean of the final interval was biased in the sense that the mean was shifted toward the endpoint that was further away.

For each surround configuration, staircase judgments were made for 50 possible infields of the same luminance, which lay in colour space on the connecting lines between the points that corresponded to the chromaticities of the colours red and green maximally realisable on this monitor. The xy-chromaticities of the line connecting the 50 infields were 0.297 and 0.600 for the green infields and 0.625 and 0.337 for the red infields, corresponding to dominant wavelengths of 549 nm and 608 nm. For each staircase the average of the last 10 settings within a convergence interval of about 2 nm dominant wavelength was taken as a measurement for the corresponding red – green equilibrium. Each data point is based on an average of 3 to 6 replications.

Each observer dark-adapted for 5 min at the beginning of the session and then adapted for 30 s to a homogeneous surround of chromaticity (0.313, 0.329) (corresponding to D65 daylight) and of luminance 10.2 cd m^{-2}. Each stimulus configuration was announced by an acoustic click and presented for 3 s followed by 7 s of inter-trial adaptation to the homogeneous D65 display (with fixation point). Each session, which comprised judgments for 12 Seurat configurations with infield of fixed luminance, lasted approximately 75 min.

6.5 *Results*
It is a well-known result that if an infield that appears to be in a red – green equilibrium at a dominant wavelength of, say, 575 nm in a neutral surround, is surrounded by a homogeneous reddish surround (with a dominant wavelength of, say, 589 nm, like the one used in our experiment), the dominant wavelength for the infield needs to be shifted towards longer wavelengths, eg to 585 nm, in order for a red – green equilibrium to be preserved. For the two observers the equilibrium settings for an equiluminous infield in a homogeneous D65 surround of 10.2 cd m^{-2} had a dominant wavelength of 575.4 nm (ER) and 574 nm (DB) respectively, and were shifted toward 586.0 nm (ER) and 585.8 nm (DB) for an equiluminous infield in a reddish homogeneous surround used.

In our experiment we found that this shift is not constant for surrounds with same space-average of colour codes but rather depends in a systematic and pronounced way on second-order statistics of the surround. The strongest shift of red – green equilibrium settings towards longer wavelengths resulted from an isochromatic surround, ie no red – green variation and spatial luminance variation only. In this condition, the red – green equilibrium settings are roughly the same as settings made with the corresponding homogeneous reddish surround. By increasing the variance of colour codes in the surround, there was, for each level of luminance modulation, a strictly monotonic decrease in the dominant wavelength of equilibrium settings in the direction of the settings made with a neutral surround. The strongest shift toward shorter wavelengths occurred on level 4 of chromatic variance for the case of an equiluminous surround, where the dominant wavelengths for a (decremental) red–green equilibrium were 579.3 nm (ER) and 580.8 (DB) for the two observers, respectively. Here, the surround seems to be almost ineffective with respect to a differential gain control. By changing the variance, while keeping the space-average fixed, a shift of almost 7 nm in the equilibrium settings of the infield can be induced. The equilibrium settings for subject ER at various levels of chromatic variation are plotted for equiluminous and decremental (2.2 cd m^{-2}) infields in figures 2a and 2b, respectively.



(a) (b)

Figure 2. Equilibrium settings (subject ER) at various levels of chromatic variation for (a) equiluminous infields and (b) decremental infields of 2.2 cd m^{-2}. See text and table 1 for precise description of the levels of chromatic and luminance variation.

It should be noted that continuity considerations require that all settings converge at the location of the data point for the homogeneous surround if luminance and chromatic variances approach zero.

The monotonic pattern of results displayed in figures 2a and 2b is qualitatively stable over a variation of several parameters (eg subjects, diameters of surround circles, decremental luminance contrast of the infield). For the spot checks of subject RM, the dominant wavelengths for the isochromatic conditions were consistently higher than those for the homogeneous conditions.

For incremental infields, however, the data pattern qualitatively differed with respect to the relative location of the settings for a homogeneous background. This difference in settings for incremental and decremental infields for a homogeneous surround is consonant with our previous findings (Mausfeld and Niederée 1993; cf also Chichilnisky and Wandell 1996; Delahunt and Brainard 2000).

In previous experiments (Mausfeld and Andres 1999) we found the same qualitative effect, ie the same rank order of settings, though quantitatively less pronounced, with an adaptation in-between trials to a homogeneous background of the same chromaticity and luminance as the Seurat configurations, and for greenish surrounds. The choice of an appropriate judgmental criterion proves to be crucial: In previous pilot experiments we had observed that the resulting data pattern was less reliable when subjects unwittingly switched between different judgmental criteria or did not make their judgments at the end of the presentation interval.

7 Discussion

Our experimental results show that the surround-dependent change in appearance of an infield in a centre – surround configuration cannot be understood as an elementary re-coding of channels by a simple surround-dependent gain control. According to traditional adaptational models, all the stimulus configurations that we used are functionally equivalent, ie are expected to exhibit the same effect on the equilibrium settings at the location of the infield. Our data clearly reveal that, in our Seurat-type configurations, surrounds with equal space-averaged Grassmann coordinates grossly violate any functional equivalence with respect to the equilibrium settings of the infield. That surrounds with the same space-average are not functionally equivalent with respect to various judgmental criteria has been frequently shown before (eg Schirillo and Shevell 1996; Andres 1997).

Jenness and Shevell (1995), also using red – green equilibrium settings for the infield, found an effect that is consonant with our findings. They compared the equilibrium settings for a reddish background of a dominant wavelength of 611 nm and a luminance of 4.5 cd m^{-2} to those of backgrounds with, respectively, sparse (5%) white and sparse green (5%) dots inserted (9 cd m^{-2}), where these backgrounds had the same space average as the homogeneous background. They found that the insertion of contextual dots caused a large (up to 15 nm) decrease in the dominant wavelength of the equilibrium settings. In their interpretation, Jenness and Shevell assumed that centre – surround configurations were processed by visual mechanisms that attempt to arrive at an estimation of an illuminant, and that the contextual elements restrict the range of possible illuminants to more neutral lights.

MacLeod and Golz (2002; Golz and MacLeod 2002), within a theoretical framework that focuses on how an illuminant can be estimated, also investigated the effects of higher-order statistics of colour codes on the transformation subserving colour constancy. Starting from considerations about chromatic information of light reflected from surfaces and their illumination-dependent changes that result from a Gaussian World model, they designed experiments, using our Seurat configurations, to test the effects of certain higher-order statistics in the surround on subjects grey settings of the infield. In their main experiment, motivated by their heuristic "When the light gets red, the reds get lighter" (to be understood as a regularity between the distal illumination and the colour coordinates of the incoming light array on which the visual system might base an inference of the illumination), they tested the effect of the correlation between luminance and redness among the colour codes of the inhomogeneous surround. For this higher-order statistic they found an influence on the grey settings consistent with their expectation derived from the interplay of surfaces and illuminations. Since all other chromatic statistics including the space average were kept constant, they interpret this finding as indication that the visual system uses this correlation statistic as a cue for the chromatic properties of the illumination.

Furthermore they performed simulations with reflectance data from a set of natural scenes (Ruderman et al 1998) and illuminants (CIE daylight spectra from 4000 K to 20 000 K correlated colour temperature) in order to investigate the illumination-dependent changes of various chromatic higher-order scene statistics (variances, correlations, skewnesses). Under their simulation conditions the correlation between luminance and redness was the only one of the statistics investigated that depended systematically on the illuminant and thus proved useful for estimating the chromatic properties of the illumination in this simulated world. This finding supports their claim derived from the Gaussian World model that this statistic may be diagnostic for the illumination. In these simulations, variations of the illumination had no consistent effect on the chromatic variance within scenes. MacLeod and Golz ascribe this lack of a systematic dependence to the fact that their illuminants (covering the range of unimpeded daylights) did not vary much in bandwidth, and conjectured that "the variance statistic could be diagnostic of a chromatically biased illuminant in more extreme cases than the ones considered".

Seurat configurations (like other configurations presented on CRT screens) instantiate incoming light arrays that can have been causally generated by quite different physical processes. Thus, it is, again, important not to confuse the physical concepts underlying a particular generation process that causally gives rise to the structure of an incoming light array with the internal concepts underlying a parsing of the incoming light array in terms of internal codes. When one prefers to discuss, as Jenness and Shevell (1995), Schirillo and Shevell (2000), MacLeod and Golz (2002) and others do, phenomena in centre – surround configurations in terms of a functional achievement that pertains to disentangling of surface and illumination properties, one has to make specific assumptions about what kinds of structural properties of an incoming light array trigger which representational primitives. Specifically, the internal representation of an 'ambient illuminant' cannot simply be derived or inductively inferred from physico-geometrical characteristics of the incoming sensory input.

The phenomena in centre – surround or Seurat configurations discussed here again indicate that however impoverished the input is, the visual systems tries to impose a structure on the sensory input that is determined by its primitives. It analyses the incoming light array in terms of its representational primitives. Because the same characteristics of a light array reaching the eye can be physically produced in many different ways, data structures pertaining to different representational primitives compete, on the basis of relevant cues, for the same input. Though the theoretical picture of the representational primitives underlying colour perception that is emerging from the available empirical and theoretical evidence is still very skeletal, and of necessity has to be based on considerable theoretical speculation, this evidence suggests that the input acts as a set of instructions, as it were, or signs for the activation of perceptual codes in terms of these primitives. In the case of colour, we have, accordingly, to distinguish colour codes that are attached to the internal concept 'surface' and colour codes that belong to an internal representation of the physical transmission medium (cf Mausfeld 2002b, for a more detailed account). These two classes subserve different functions and exhibit different coding properties. The coding properties pertaining to the concept of the 'ambient illumination' or the transmission medium resemble, and probably are related to, coding properties of the 'ground' in figure – ground segmentations. Relevant observations date back to Fuchs (1923), who observed that the colour of afterimages can depend on the way identical input configurations have been segregated into figure or ground, and to Gelb and Granit (1923), who showed that for identical stimulus configurations hue thresholds are higher when the relevant portion of the configuration is regarded as figure than when it is regarded as ground. These effects, of what traditionally has been described as 'field organisation', mirror the way different data structures compete for the same input. In this process, specific physico-geometrical properties of the incoming light array trigger two kinds of representational primitives and modulate their interplay by a specific class of parameterised transformations. We interpret, within the theoretical perspective outlined above, our experimental data as providing evidence that second-order statistics of chromatic codes of a *single* view of a 'scene' can act as corresponding modulating parameters. More specifically, the shift in dominant wavelength of red – green equilibrium settings of the infield exhibited a stable and strong dependence on the chromatic variance of the surround, in the sense that incoming light arrays with very low variation in chromatic codes tend to be interpreted as being caused by scenes that are viewed under illuminations that chromatically deviated from a neutral one, whereas light arrays with high variation in chromatic codes tend to be interpreted as being caused by scenes that are viewed under 'normal' illumination. Thus, low chromatic variances resulted in a tendency toward 'illumination invariance' of the infield, high variances in a tendency toward 'scene invariance'. Observers also noted that in the latter case, but not in the former, the surround circles appear as solid taut surfaces, in line with Gelb's (1929/1938) observation that "the phenomenal impressions of 'proper' colour of surfaces and 'normal' illumination intimately correspond to each other".

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Appendix

This appendix briefly describes how the surrounds of Seurat configurations can be constructed. For a more detailed account see Andres (1997). The description is based on CIE space. But it will become clear that the procedure also works in other colour spaces, and that critical features of the resulting surrounds can easily be transformed to colour spaces linearly related to CIE colour space.

For a given geometry of the surround (overlapping circles) the task is to assign colours (specified by CIE coordinates) to these circles such that several conditions are satisfied. First, the average of the colours of the pixels of the surround as well as the averages in several circular rings have to be equal to a prescribed colour $\boldsymbol{a}$. Second, the covariance matrix of the colours of the pixels has to be equal to a given positive definite matrix $\mathbf{K}$.

The desired covariance matrix $\mathbf{K}$ is characterised by its eigenvalues and eigenvectors which have an intuitive geometric meaning: Chebyshev's inequality, eg, shows that the relative number of pixels, whose colours are within an ellipsoid centred at the average with main axes in the direction of the eigenvectors and main radii equal to k times the roots of the eigenvalues, is at least $1 - 3/k^2$. So these ellipsoids give a rough idea of the form of the cloud of the colours of the pixels. If, eg, the second and third eigenvalues are negligible in comparison to the first, the colours of the pixels will practically lie on a line through the average in the direction of the first eigenvector.

Since eigenvectors and eigenvalues are not transformed in an easy way when the coordinate system is changed, the choice of this system seems to be a critical point. In the case where two eigenvalues are negligible in comparison to the first, however, the first eigenvector of the transformed colour values will not differ significantly from the transformed first eigenvector as long as the linear transformation is reasonable. The same argument applies to the case of one small eigenvalue: here the plane spanned by the first two eigenvectors of the transformed values will practically coincide with the linearly transformed plane spanned by the first two original eigenvectors.

At the beginning of the procedure the surround is randomly covered with overlapping disks of a given diameter. In the first step, every disk is randomly assigned a number between 1 and n, where n is the number of colours to be used. Now, every pixel of the surround is assigned a number which is a code for the colour the pixel is to be given: either the pixel belongs to some disk, in which case it is assigned the number of this disk, or it is assigned the number $n + 1$.

In the next step the numbers d_{0i} of pixels of the surround with code i are counted ($i = 1, ..., n + 1$). The vector $\boldsymbol{f}_0$ of length $n + 1$ is defined to consist of the components d_{0i}/N ($i = 1, ..., n + 1$), where N is the number of pixels in the surround. It is the vector of the relative frequencies of pixels of colour i. In a similar way one obtains vectors $\boldsymbol{f}_j$ of the relative frequencies of the colours in the jth circular ring for $j = 1, ..., J$, where J is the number of these rings.

Now, the conditions for the colours of the surround can be formulated in these terms. Let $\mathbf{C}$ be the $\big((n + 1) \times 3\big)$ matrix containing as rows the colour coordinates corresponding to the codes 1, ..., $n + 1$. Then the average of the colours is given by the row vector $\boldsymbol{f}_0{}'\mathbf{C}$. Similarly, the average in the jth circular disk is given by $\boldsymbol{f}_j{}'\mathbf{C}$. If $\boldsymbol{e}_{n+1}$ is the vector $(0, ..., 0, 1)'$ then $\boldsymbol{e}_{n+1}'\mathbf{C}$ gives the colour of that part of the surround that is not covered by the disks. If $\boldsymbol{a}$ is the vector of the desired average, then the conditions $\boldsymbol{f}_j{}'\mathbf{C} = \boldsymbol{a}'$ ($j = 0, ..., J$), and $\boldsymbol{e}_{n+1}'\mathbf{C} = \boldsymbol{a}'$ mean that the average of the colours of the surround and of each circular ring has coordinates $\boldsymbol{a}$ as does the colour of that part of the surround that is not covered by the disks.

If $\mathbf{D}$ is the diagonal matrix, the entries of which are the components of $\boldsymbol{f}_0$, then the covariance matrix of the colour coordinates of the surround is given by $(\mathbf{C} - \boldsymbol{1}\boldsymbol{f}_0'\mathbf{C})'\mathbf{D}(\mathbf{C} - \boldsymbol{1}\boldsymbol{f}_0'\mathbf{C})$ [with $\boldsymbol{1} = (1, ..., 1)'$]. The last requirement is that this matrix should be equal to a given covariance matrix $\mathbf{K}$ which is supposed to be positive definite.

In order to construct a matrix $\mathbf{C}$ fulfilling these conditions, one starts with an $\big((n+1) \times 3\big)$ matrix $\mathbf{X}$ of random numbers. The columns of this matrix are made orthogonal to all the vectors $\boldsymbol{f}_j$ $(j = 0, ..., J)$ and to the vector $\boldsymbol{e}_{n+1}$. Let the resulting matrix be $\mathbf{Y}$. Now one finds (3×3)-matrices $\mathbf{U}$ and $\mathbf{V}$ such that $\mathbf{K} = \mathbf{U}'\mathbf{U}$ and $\mathbf{Y}'\mathbf{D}\mathbf{Y} = \mathbf{V}'\mathbf{V}$ (take, eg, the Choleski decomposition). Supposing that $\mathbf{V}$ is regular, one sets $\mathbf{C} = \mathbf{Y}\mathbf{V}^{-1}\mathbf{U} + \boldsymbol{1}\boldsymbol{a}'$.