

Perceptual and computational aspects of color constancy

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PERCEPTUAL AND COMPUTATIONAL ASPECTS OF COLOR CONSTANCY

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J.M. Troost

PERCEPTUAL AND COMPUTATIONAL ASPECTS OF COLOR CONSTANCY

*Een wetenschappelijke proeve
op het gebied van de Sociale Wetenschappen,
in het bijzonder de Psychologie*

Proefschrift

ter verkrijging van de graad van doctor
aan de Katholieke Universiteit te Nijmegen,
volgens besluit van het College van Decanen
in het openbaar te verdedigen
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door

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VOORWOORD

De open en informele sfeer binnen het NICI die ik als zeer stimulerend heb ervaren heeft er in belangrijke mate toe bijgedragen dat dit proefschrift zonder het hoeven nemen van noemenswaardige hindernissen tot stand is gekomen. Nog belangrijker hiertoe was dat ik het vak in de voor mij juiste verhouding van zelfstandigheid en samenwerking heb kunnen leren van Charles de Weert. Ik ben hem zeer dankbaar.

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CHAPTER 1

INTRODUCTION¹

Under normal circumstances, color is often regarded as an invariant property of objects, irrespective of changes in illumination. If one is asked to describe an object, one will almost certainly mention its color, along with properties as size and shape. Even at low luminance levels, under which color perception is poor, colors are assigned to objects. This understanding of color is reflected spontaneously in the communication about the objects that surround us. However, in color science, color is considered as a perceptual, rather than a physical property of objects. This understanding goes back to Newton (1730/1952), who discovered that light is energy propagated in the form of electromagnetic waves (of different lengths), rather than being colored itself. It implies that to perceive color, the human visual system needs a receptor mechanism that can discriminate radiant energy of different wavelengths. One possibility would be the existence of a large number of receptors, each sensitive for a different wavelength, but as Young (1807) anticipated, this would not be compatible with the high spatial resolution of the visual system. Therefore, he proposed a reduction to three receptor classes that was later used by Helmholtz (1867/1962).

Helmholtz' theory of trichromatic color vision can be considered as one of the first in which sensations were directly related to neurophysiological activities in the periphery of the visual system. Though trichromacy explains why some wavelength distributions can be distinguished from others, it does not explain color appearance. By assuming elementary sensations, connected to the activity of photoreceptors, it is possible to account for the color appearance of a spectrum. According to Helmholtz, color appearance is the additive mixture of elementary color sensations red, green and blue, which result from corresponding activities in the long, middle and short wave sensitive classes of photoreceptors, respectively. A red object, for example, exciting the long wave sensitive cones more than the middle long and short wave cones, would signal more redness than greenness and blueness, thereby establishing the impression of a red hue. Indeed, to some degree color appearance can be described by relating it in a simple way to absolute amounts of activity in the photoreceptors. This is certainly the case when color is observed through an aper-

¹ This chapter partly appears in Troost, J. (1992) De waarneming van objectkleur [The perception of object color] *Nederlands Tijdschrift voor de Psychologie*, 47, 15-23.

ture, that is, without surroundings. However, the relation between color appearance and receptor activities is completely lost when objects are viewed in their natural environments. Especially under conditions where illuminant changes are involved and the visual system shows color constancy, Helmholtz' theory of trichromatic color vision fails to explain the color appearance of objects. Helmholtz, who was well aware of this problem, came up with another explanation of the perception of object color, i.e. color constancy, but this alternative, being too cognitivistic, was never considered as a convincing explanation by the scientific community, including Helmholtz himself. Perhaps the best way to illustrate Helmholtz' problems with color constancy is to describe a demonstration provided by Land more than a hundred years later (Land, 1977).

Consider two collages of a large number of matte colored papers, each illuminated by a red, green and blue narrowband light source. By means of a photometer in conjunction with filters having spectral transmittance closely resembling the spectral sensitivity of the human cone systems, it is possible to measure the amount of light absorbed by each of the three classes of photoreceptors at every point in each single collage. Suppose that the three receptor absorbances are registered for some paper, the standard, in the first collage, giving the impression of a green hue for example. Land now moved to the other collage, focused at some arbitrarily chosen paper, the test, and adjusted each of the other set of three light sources separately until the same amounts of radiant flux were obtained as in the standard paper from the first collage. When all three light sources were adjusted, they were turned on together. Note that because the activities in the receptors are the same for both the standard and test papers, Helmholtz would have predicted that both papers will have the same color appearance. However, the actual color appearance of the test will be anything, indicating that it is not the absolute amount of light reaching the eye that determines the final color percept.

The most easily conceivable way to achieve color constancy seems to be to calculate the surface reflectance of objects, simply because this is the only relevant physical property of an object that is invariant under illuminant changes. The calculation of surface reflectance by the visual system, however, is by no means a trivial case. For example, attribution of the pattern of light reaching the eye, the only external information that is available to the visual system, to illuminant and object components is indeterminate. Sensory color is dependent on the spectral characteristics of both the current illuminant and the reflectance of the object under consideration. So, to achieve perfect color constancy, the visual system has to get rid of the illuminant component first.

Now, before the illuminant component can be eliminated it has to be known by the visual system. Helmholtz proposed that the illuminant component in the light reaching the eye is judged at a central level in the visual system, judgements being based on past experience. Once the illuminant has been recognized, the visual system determines the color of an object by making unconscious inferences, thereby discounting the illuminant. A white object casted by a shadow, for example, is perceived as being lighter than an equally bright object under direct illumination because the visual system has learned that shadows reduce the brightness of objects.

The problem with this explanation is that it contains a circular argument, that is, knowledge of the illumination characteristics can only be obtained on the basis of perceived colors. But perceived colors themselves are assumed to be the product of unconscious inferences. The empirical view on color constancy, and more specifically the importance of judgements, held by Helmholtz did never become popular. In fact, Helmholtz' contemporary Hering already stated that "one must not represent as products of experience the same innate functions of the visual system on the basis of which these experiences were originally acquired" (Hering, 1874/1962, p.21). Hering proposed a more sensory oriented type of explanation, based on pupillary adjustment, retinal adaptation and contrast, and his ideas about the latter two have been most influential since the last two to three decades in which Land initiated new interests in the color constancy phenomenon (Land, 1959, 1977, 1986a; Land & McCann, 1971). In addition, Hering was well aware that peripheral processes cannot fully account for color constancy. Therefore, he introduced the concept of memory colors that are based on past experiences and can be aroused by other non-color characteristics of an object. The color appearance of an object then, is both based on the peripheral color sensation and the memory color for that object. So, although Hering was very reluctant to refer to central factors in his explanation for color constancy, and strongly opposed Helmholtz for doing so by stressing the importance of receptor adaptation and contrast, the theoretical status of Hering's memory colors is similar to that of Helmholtz' unconscious inferences. Both Helmholtz and Hering recognized the importance of judgements based on past experiences, but their willingness to incorporate these central factors in a theory about color constancy clearly differed.

Although the dispute about central mechanisms is in fact still actual, it has led to an unfavorable divergence in the literature about color constancy between those who accept the relevance of (non-sensory) processing of informational cues of illumination and/or objects (e.g., Adelson & Pentland, 1990; Beck, 1972; Gilchrist, Delman, & Jacobsen, 1983; Rock,

1977) and those who do not (e.g., Dannemiller, 1989; Grossberg & Todorović, 1988; Land, 1977; Werner and Walraven, 1982). The color constancy issue about the importance of sensory processes returns in all chapters of this dissertation, chapter 2 being an exception.

First, in Chapter 3 the classical paradigm of color matching is discussed in relation to color naming. It is argued that whereas a matching task can be used to give an estimation of the contribution of sensory processes, i.e. chromatic adaptation and lateral inhibition, to color constancy, it ignores the identification aspects that can easily be studied when applying a naming task.

In Chapter 5 the relevance of a computational model, i.e. the Sällström-Buchsbaum model (after the originators Sällström (1974) and Buchsbaum (1980)), to human color constancy is discussed. The Sällström-Buchsbaum model is based on operations that automatically eliminate the illuminant component in the pattern of light reaching the eye, and, if applied to human vision, can therefore be considered as a modern representative of sensory explanations.

A formal description of the Sällström-Buchsbaum model, among other models that can be used to predict object color shifts due to changes in illumination, is given in Chapter 4. This chapter also deals with metamerism, a phenomenon that has to do with the trichromacy of the human visual system, which means that only three receptor classes are available to respond to the pattern of incoming light. The question is how the visual system can reconstruct a continuous spectrum if color is described by only three quantities. Even if discrete samples of the continuous spectra are taken, a relatively large number of (equally spaced) samples is required to approximate the original spectrum. So, an unsolvable set of equations is obtained because only three known quantities, i.e. receptor outputs, are available to reconstruct the discrete spectrum that consists of a much larger number of unknowns. Indeed, mathematically the number of possible spectra having the same three parameter representations, called metameres, is unlimited. So, which spectrum is chosen, depends on the type of theoretical constraint that is put on the mathematical set of possibilities.

Finally, the epilogue addresses lines of future research in color constancy. More specifically, the relevance of the figural organization of scenes, that was already anticipated by Koffka (1935), will be discussed. In a sense, the importance of central factors, which was emphasized by Helmholtz and recognized, but ignored, by Hering, will be stressed.

CHAPTER 2

BINOCULAR MEASUREMENTS OF CHROMATIC ADAPTATION¹

In traditional three receptor theory (Helmholtz, 1867, 1962) the color of an object is solely determined by the absolute amount of light that is reflected from the object to the eye. In Helmholtz's view each of the three receptor systems that he postulated was responsible for one elementary color sensation (red, green or blue). These receptors were identified, by micro spectrophotometric methods (for a review see Bowmaker, 1984), nearly 100 years later as the long (L), middle long (M) and short (S) wavelength sensitive cones. According to Helmholtz a blue object simply resulted in a larger elementary sensation of blue than of red and green, thereby establishing its blue appearance. Because the same correspondence holds for differently colored objects, Helmholtz succeeded in connecting elementary sensations to physiological response mechanisms. However, there is a serious problem, of which Helmholtz was well aware, with this theory. It can not account for the most fundamental phenomenon of color perception, namely color constancy. Whereas one tends to see an object as having invariant color, despite variations in illumination, the light that is reflected from an object to the eye is also dependent of the light that is sent from an illuminant to the object. Therefore, the elementary sensations, determined by receptor responses, have an object and an illuminant component. To the extent that color perception is independent of illumination it seems to mean that the visual system somehow gets rid of the illuminant component in the light reaching the eye. Helmholtz himself did not specify a mechanism that accomplishes this elimination, but later von Kries (von Kries, 1905) formulated an adaptation model that can deal to some extent with illuminant changes (for a detailed discussion see Worthey & Brill, 1986).

Von Kries proposed that the spectral sensitivities of the three receptor systems can be varied by a constant that is inversely related to the level of adaptation. Thus, the sensitivities are taken to be variable, rather than fixed as Helmholtz supposed. If, for example, the adapting light is yellowish, the sensitivities of the L-wave and M-wave cones are supposed to decrease, while the S-wave cone sensitivity increases. By taking the illuminant chromaticity as the adaptation level it is possible to obtain illuminant invariant color descriptors. Unfortunately, however, the illuminant chromaticity is unknown to the visual system because in most situations the visual system has no direct information

¹ Troost, J., & de Weert, Ch. (submitted). *Vision Research*.

about the illuminant. Therefore, it has to be estimated from the pattern of light reaching the eye. The average color in a scene is often used as an estimator for this (e.g., Brill & West, 1986; Helson, 1938; Land, 1977, 1986a). Once the adaptation level is known the von Kries coefficients can be obtained with which receptor responses have to be multiplied in order to make predictions. Formally,

$$L' = a_L L,$$

$$M' = a_M M,$$

$$S' = a_S S,$$

where L , M and S are receptor outputs, specifying the color of a particular area under a particular adaptation level, and L' , M' and S' the corresponding quantities for the same area under another adaptation level. The relation between the two levels of adaptation is expressed by the von Kries coefficients a that are defined as,

$$a_L = \frac{L'_\text{AVG}}{L_\text{AVG}},$$

$$a_M = \frac{M'_\text{AVG}}{M_\text{AVG}},$$

$$a_S = \frac{S'_\text{AVG}}{S_\text{AVG}}.$$

Unfortunately von Kries' adaptation model does not describe how to obtain the adaptation level. The model only describes the relation between the adaptation level and the receptoral responses. The only theory that gives an explicit method to obtain the adaptation level is Land's Retinex Theory (Land, 1977, 1986a) that provides an algorithm to obtain the von Kries coefficients. Nevertheless, von Kries' coefficient rule is still widely used although in different formulations (e.g., Bartleson, 1980; Buchsbaum & Gottschalk, 1983; Dannemiller, 1989; Land, 1977, 1986a) and sometimes with improvements in order to fit empirical data (e.g., Lucassen & Walraven, 1991; Takahama, Sobagaki & Nayatani 1984; Richards & Parks, 1971).

This chapter is mainly concerned with the relation between the extent of adaptation that is obtained and the difference in chromaticity between the average color of a stimulus configuration, i.e., the adaptation level, and target colors. An extra motivation was an effect reported by Tiplitz Blackwell and Buchsbaum (1988). They found chromatic induction to be a function of the color difference between a target color and its surround, with a

peak when the common signal of target and surround is large. As Tiplitz Blackwell & Buchsbaum argue, this effect can easily be related to chromatic adaptation or color constancy. Under normal viewing conditions, the common signal in the pattern of light reaching the eye is partly due to the illuminant component (see also Land, 1977, 1986a). Of course the range of colors that is found under different adaptation levels, i.e., illuminant conditions, is limited in the natural image. For the eye adapted to a bluish illuminant for example, it is very unlikely that an area with a color that lies outside this range, like a deep yellow, belongs to an object. It is much more likely that this area will be perceived as self luminous. This is analogous to the effect first described by Gelb (1929). If a piece of dark paper is locally illuminated by a slide projector in an otherwise darkened room, the dark paper looks as a bright self luminous object. Clearly, the difference between the locally illuminated paper and the darkened surround is too large for the human visual system to perceive both target and surround as having the same quality, that is, as objects. The question is to what extent receptor adaptation, the first stage of visual processing, is affected by the difference in color between target and surround. Or, to put it more general, has the mechanism of receptor adaptation evolved towards the limited range of colors in the natural image.

This question has been tested in nine different asymmetric matching experiments in which the difference between the target color and surround color was varied. Every experiment dealt with a different level of adaptation. The results are displayed in $u'v'$ -chromaticity space. Additionally, the performance of a few models that can be considered as modifications of von Kries' coefficient rule were compared.

METHODS

A binocular asymmetric matching method was used. Two configurations of 19 hexagons, identical in shape, size and duration, but of different hue, saturation and luminance, were presented alternately to the left and right eye. With foveal vision the left and right eyes were adapted to different conditioning stimuli. The purpose of employing an alternating presentation method was to prevent any possible direct interocular transfer of chromatic adaptation levels.

Stimuli

The stimulus configuration employed in the experiment is shown in Figure 1. The left grid of hexagons is presented to the left eye, the right grid to the right eye.

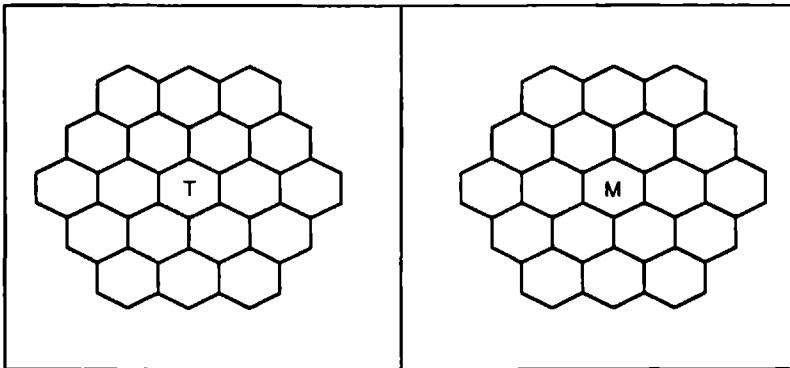


Figure 1. Stimulus configuration used in the asymmetric binocular matching experiments. The left configuration of hexagons was presented to the left eye only. Its central hexagon, T, is the test field. The configuration, presented to the right eye only, was the D65 reference field. The right central hexagon, M, served as the matching field.

Both grids are composed of geometrically identical and adjacently arranged hexagons, as opposed to uniform fields as often used. The left and right grids of hexagons, serving as adapting fields, will be referred to as test and reference field, respectively. Consequently, the central hexagon in each test and reference field is referred to as the test and reference stimulus, respectively. The remainder of the CRT was dark. The luminance of each hexagon forming an adapting field varied in luminance between 8 and 12 cdm⁻² to avoid difficulties with edge discrimination that occur under isoluminant conditions. However, the average luminance in both test and reference fields was kept at 10 cdm⁻². Each individual hexagon position had the same assigned luminance in both test and reference fields to obtain identical luminance contrast conditions. The 18 reference field hexagons all had the chromaticity of D65, so they differed only in luminance. The 18 test field hexagons varied in chromaticity and had an average chromaticity (arithmetic and geometric average

chromaticity of the test field hexagons were equal) corresponding to a red, green and blue stimulus. Thus, three adapting conditions were studied. The average chromaticity coordinates are listed in Table 1 and plotted in Figure 2. The colors of the 18 test field hexagons were selected according to the following procedure. First, the average chromaticities of the red, green and blue test fields were chosen. Next, each test field was assigned a color that differed 0.015 to 0.0225 u', v' -chromaticity units from the average chromaticity. The average chromaticity of the 6 test field hexagons that were adjacent to the test stimulus (the inner "ring") was made equal to the average chromaticity of the 12 non-adjacent test field hexagons (the outer "ring"). In this way, effects that can possibly be due to spatially weighting of surrounding colors were avoided.

Table 1

Red (a), green (b) and blue (c) test field colors in CIE 1976 u', v' -chromaticity coordinates. Test stimuli are given in the first two columns. On the corresponding two rows the averages (up) and standard errors (below) are given for the euclidean distances between test stimulus and match ($d_{(u',v')}$) and u', v' of the matches for the 5, 10, and 25 cdm⁻² luminance conditions respectively.

RED TEST FIELD (u', v') = (0.350, 0.468)

test stimulus			color match							
u'	v'	$d_{(u',v')}$	5cdm ⁻²		10cdm ⁻²		25cdm ⁻²			
			u'	v'	$d_{(u',v')}$	u'	v'	$d_{(u',v')}$	u'	v'
0.140	0.468	0.016	0.136	0.481	0.009	0.135	0.473	0.007	0.138	0.471
		0.003	0.002	0.004	0.002	0.001	0.003	0.002	0.001	0.003
0.170	0.468	0.039	0.139	0.488	0.028	0.149	0.475	0.015	0.157	0.470
		0.003	0.002	0.005	0.003	0.007	0.002	0.003	0.004	0.001
0.200	0.468	0.046	0.157	0.481	0.031	0.171	0.474	0.013	0.192	0.469
		0.004	0.004	0.004	0.004	0.005	0.002	0.001	0.003	0.001
0.230	0.468	0.055	0.176	0.479	0.031	0.199	0.469	0.028	0.213	0.471
		0.006	0.006	0.002	0.002	0.002	0.000	0.004	0.009	0.002
0.260	0.468	0.069	0.193	0.480	0.047	0.213	0.469	0.033	0.235	0.471
		0.006	0.005	0.003	0.006	0.006	0.000	0.006	0.009	0.001
0.290	0.468	0.074	0.217	0.470	0.072	0.218	0.469	0.037	0.254	0.474
		0.003	0.003	0.003	0.007	0.007	0.000	0.007	0.007	0.002
0.320	0.468	0.085	0.236	0.465	0.095	0.225	0.468	0.044	0.276	0.473
		0.006	0.006	0.005	0.008	0.008	0.000	0.006	0.006	0.002
0.350	0.468	0.096	0.255	0.466	0.069	0.281	0.469	0.042	0.309	0.472
		0.006	0.006	0.003	0.007	0.007	0.001	0.008	0.008	0.002
0.380	0.468	0.075	0.307	0.473	0.060	0.320	0.471	0.048	0.333	0.474
		0.008	0.009	0.004	0.006	0.006	0.001	0.007	0.007	0.003

GREEN TEST FIELD (u',v') = (0 144, 0 529)

test stimulus			color match								
u'	v'	$d_{(u'v')}$	5cdm ²			10cdm ²			25cdm ²		
			u'	v'	$d_{(u'v')}$	u'	v'	$d_{(u'v')}$	u'	v'	$d_{(u'v')}$
0 120	0 558	0 042	0 153	0 533	0 037	0 144	0 534	0 033	0 144	0 536	
		0 004	0 003	0 004	0 004	0 003	0 006	0 004	0 001	0 004	
0 132	0 544	0 044	0 165	0 517	0 036	0 159	0 525	0 026	0 152	0 527	
		0 005	0 002	0 007	0 004	0 003	0 006	0 002	0 001	0 002	
0 144	0 529	0 040	0 172	0 501	0 032	0 168	0 513	0 027	0 162	0 510	
		0 005	0 002	0 005	0 006	0 004	0 006	0 002	0 001	0 002	
0 156	0 516	0 041	0 185	0 490	0 037	0 184	0 498	0 023	0 172	0 500	
		0 006	0 003	0 007	0 004	0 003	0 007	0 002	0 002	0 001	
0 168	0 502	0 039	0 197	0 477	0 028	0 190	0 486	0 022	0 183	0 486	
		0 002	0 000	0 003	0 006	0 004	0 004	0 003	0 002	0 003	
0 180	0 489	0 030	0 203	0 472	0 020	0 195	0 476	0 020	0 193	0 473	
		0 003	0 001	0 006	0 004	0 002	0 003	0 001	0 002	0 001	
0 192	0 474	0 025	0 211	0 460	0 013	0 202	0 466	0 015	0 201	0 462	
		0 003	0 000	0 005	0 004	0 003	0 003	0 002	0 001	0 002	
0 204	0 460	0 016	0 219	0 458	0 015	0 215	0 452	0 013	0 211	0 450	
		0 001	0 001	0 003	0 004	0 003	0 003	0 002	0 001	0 003	
0 216	0 447	0 015	0 228	0 446	0 010	0 225	0 445	0 013	0 223	0 436	
		0 002	0 002	0 004	0 002	0 002	0 001	0 002	0 001	0 002	

BLUE TEST FIELD (u',v') = (0 198, 0 303)

test stimulus			color match								
u'	v'	$d_{(u'v')}$	5cdm ²			10cdm ²			25cdm ²		
			u'	v'	$d_{(u'v')}$	u'	v'	$d_{(u'v')}$	u'	v'	$d_{(u'v')}$
0 198	0 243	0 029	0 199	0 272	0 030	0 196	0 268	0 038	0 195	0 281	
		0 005	0 000	0 005	0 012	0 002	0 014	0 009	0 000	0 009	
0 198	0 273	0 045	0 198	0 313	0 030	0 198	0 303	0 041	0 196	0 313	
		0 008	0 002	0 010	0 017	0 001	0 017	0 007	0 001	0 007	
0 198	0 303	0 072	0 198	0 374	0 052	0 203	0 340	0 048	0 195	0 351	
		0 010	0 001	0 011	0 014	0 004	0 022	0 006	0 000	0 006	
0 198	0 333	0 101	0 202	0 434	0 079	0 199	0 411	0 056	0 198	0 389	
		0 009	0 002	0 009	0 025	0 001	0 025	0 006	0 000	0 006	
0 198	0 363	0 107	0 201	0 470	0 089	0 201	0 452	0 062	0 198	0 425	
		0 007	0 001	0 007	0 012	0 000	0 012	0 005	0 000	0 005	
0 198	0 393	0 107	0 201	0 500	0 077	0 201	0 470	0 062	0 198	0 455	
		0 008	0 002	0 008	0 005	0 001	0 005	0 006	0 000	0 006	
0 198	0 423	0 102	0 199	0 524	0 075	0 201	0 498	0 052	0 200	0 475	
		0 006	0 004	0 005	0 004	0 003	0 004	0 005	0 001	0 005	
0 198	0 453	0 072	0 204	0 525	0 067	0 204	0 519	0 048	0 199	0 501	
		0 005	0 002	0 005	0 004	0 004	0 004	0 004	0 000	0 004	
0 198	0 483	0 051	0 201	0 533	0 048	0 206	0 529	0 046	0 201	0 528	
		0 005	0 002	0 006	0 009	0 003	0 010	0 002	0 001	0 002	

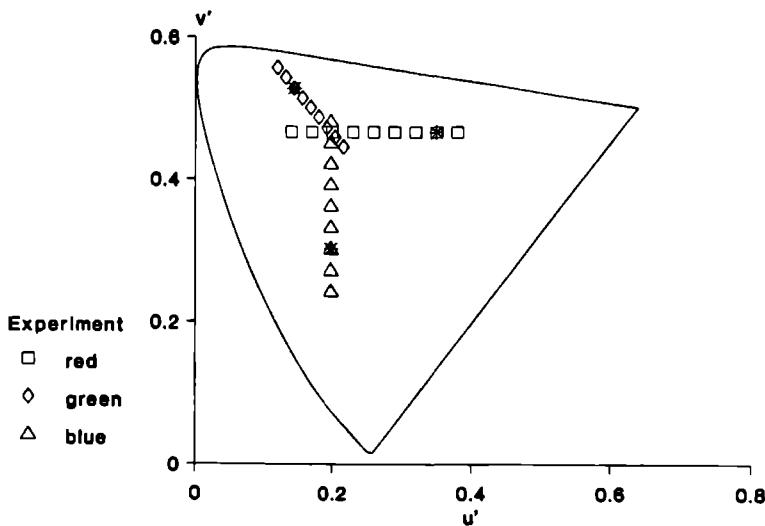
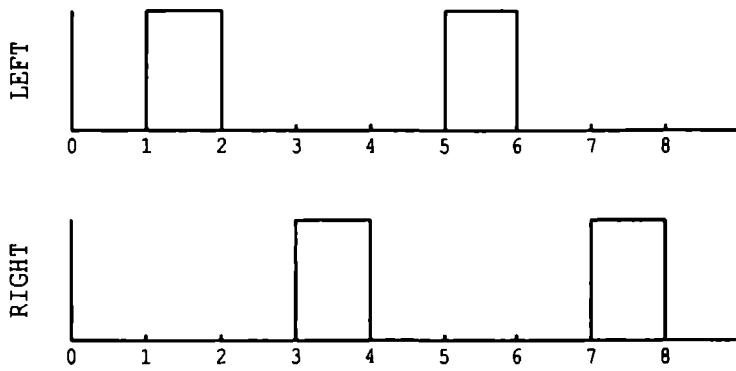


Figure 2. Graphical presentation of chromaticity coordinates of all stimuli and average surrounds (asterisks) in CIE 1976 u',v' color space.

The coordinates of the three sets of test stimuli, one for each adapting condition, are also listed in Table 1 (first two columns) and plotted in Figure 2. The test stimuli were presented at three luminance levels (i.e., 5, 10, and 25 cdm^{-2}) to investigate whether the qualitative difference in appearance of stimuli below or above the adapting luminance, that is, the average luminance of the adapting fields (10 cdm^{-2}), can be quantified. Stimuli above the adapting luminance often appear as self-luminous, below they appear as pseudo-object colors.

The visual angles of the central hexagon and the whole configuration were 0.95° and 4.77° respectively at a viewing distance of 1.2 meters. So, both reference and test stimuli were imaged in the foveal area in the corresponding eye.

The temporal relationship between the test and matching stimulus is shown in Figure 3.



PRESENTATION OF THE STIMULI OVER TIME IN SECONDS

Figure 3. The temporal relationship of the presentation of adapting and standard configurations.

In every cycle both test and matching stimuli were displayed on the monitor screen for 1 second and there was a 1 second period of darkness between them. The duration of the darkness interval was chosen so that a match could easily be made without a too strong demand on memory at the one hand, but long enough to avoid binocular interaction on the other hand.

Apparatus

Stimuli were presented on a high resolution color CRT monitor, type Barco CVTM2/51H, connected to a minicomputer (type PDP 11/23). The three phosphors have chromaticities: R, $x = 0.654$, $y = 0.341$; G, $x = 0.285$, $y = 0.606$; B, $x = 0.154$, $y = 0.061$. The eight parallel graphic point video memories (matrix MSII 512) can address 512×512 pixels. 256 different colors can be displayed at once. With 3×256 color registers (10 bits resolution) $1024 \times 1024 \times 1024$ different colors can be realized. The luminance values of each color gun of the monitor were measured with a Pritchard Spectra Photometer. (For details of the equipment see Wittebrood, Wansink and de Weert, 1981).

Programs were available for automatic stimulus presentation and data collection. Three pairs of buttons were available to adjust the color of the reference stimulus, two pairs for

changing chromaticity coordinates and another pair for changing the luminance. Each pair of buttons had one for decreasing and the other for increasing the corresponding quantity.

A mirror system, with a septum in the middle, was placed in front of the monitor screen (see Figure 4) to present the test field to the left eye only, and the reference field to the right eye only.

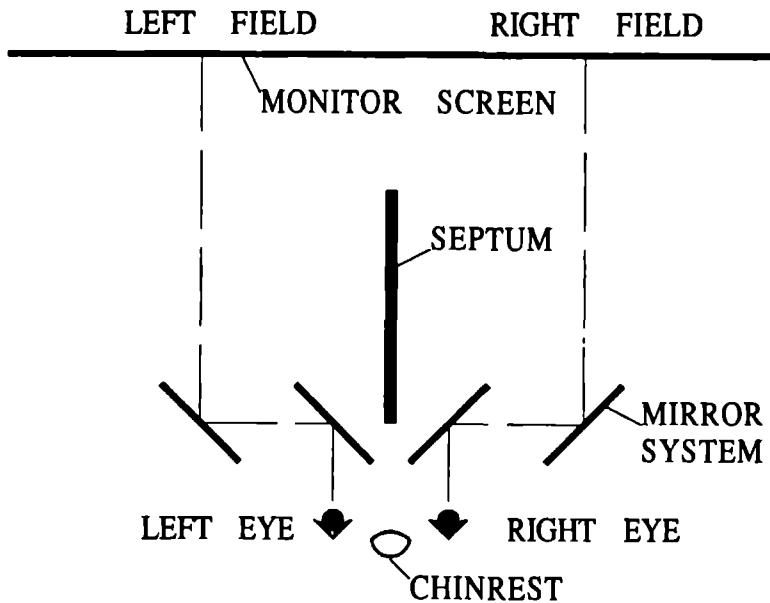


Figure 4. Schematic diagram of the binocular presentation system.

In this way each eye was adapted to different conditioning stimuli. A chin rest was used for the fixation of the subject's head during the experiment. The left and right eye images were presented at corresponding retinal positions.

Procedure

Nine different experiments were carried out. In each experiment one of three different adapting fields, giving subjective impressions of red, green and blue respectively, and one of three luminance levels of the test stimuli (5 , 10 , and 25 cdm^{-2}) was used. The nine different test stimuli were repeated three times and presented in random order. Hence each experimental session consisted of 27 experimental trials and lasted approximately 40 minutes. The color of each adapting field hexagon was randomly arranged to one of

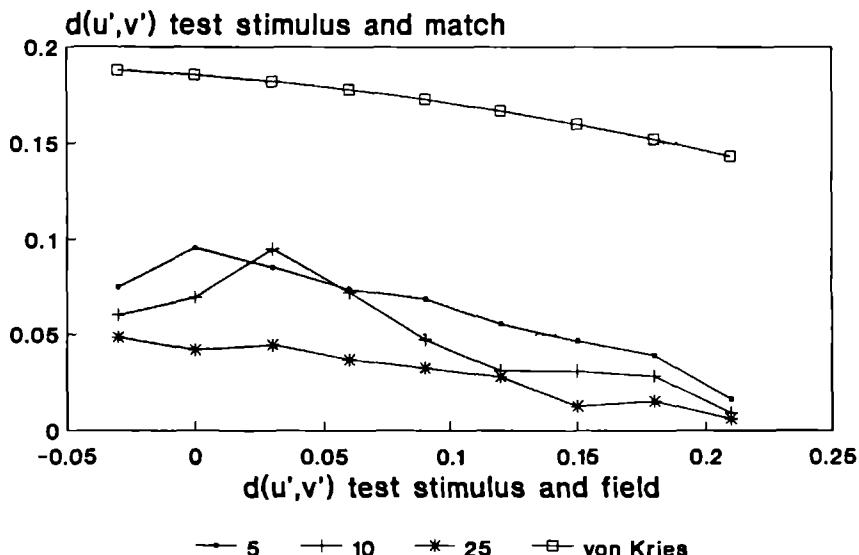
the surrounding positions (for the inner and outer ring separately) and randomly rearranged in the next experimental trial. However, the luminance contrast correspondence between reference and test field was preserved.

Before each experiment, subjects fixed their heads by means of the chin rest and adjusted the mirrors so that the corresponding fixation marks of each field coincided binocularly. The subjects' eyes were adapted to test and reference conditioning stimuli and dark background for several minutes. Subjects were instructed to adjust the color of the reference stimulus until it matched the color of the test stimulus. When a match was made the subject pushed a button, the result was stored on disk and the next stimulus was presented. The visual judgment was generally extended over several numbers of cycles so that any initial disturbance was eliminated.

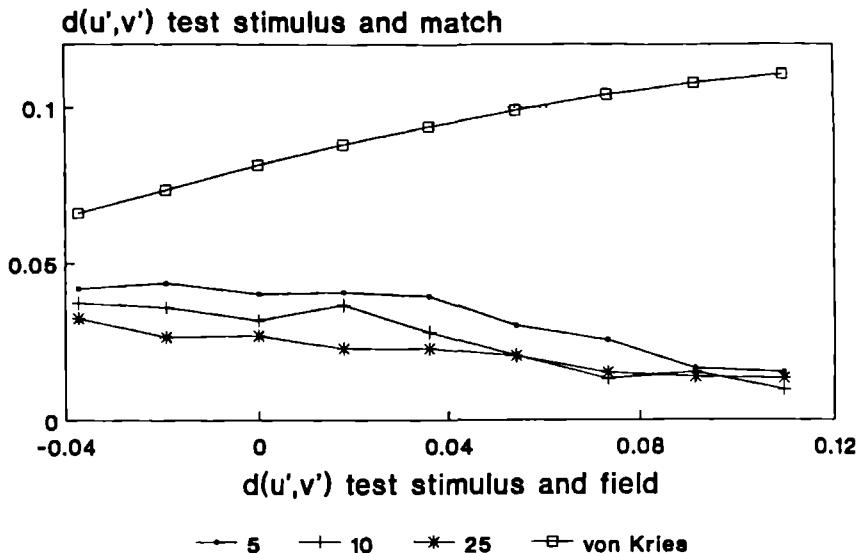
Subjects

Six subjects participated in the experiment, three of them being the authors, L.W., J.T. and C.W., the others undergraduate psychology students, who were experienced color matchers but naive to the purpose of the experiment. They all have normal color vision, as determined with the Ishihara pseudo-isochromatic plates test and the Farnsworth-Munsell 100-hue test.

red test field



green test field



blue test field

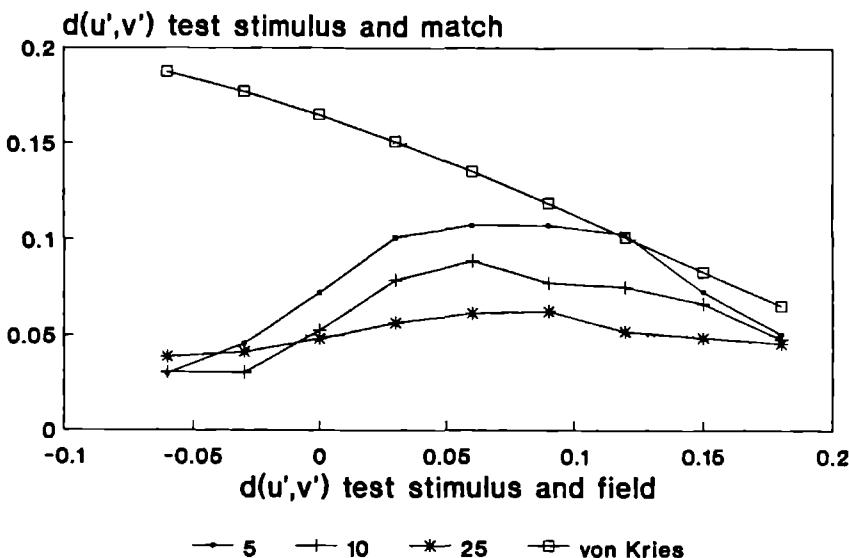


Figure 5. The observed difference between test stimulus and match plotted against the difference between test stimulus and test field for the red (a), green (b) and blue (c) test fields. Both abscissa and ordinate show the distances between two colors in u',v' -chromaticity space. Each symbol in the plot is the average of three matches done by two or three subjects. Standard errors can be found in Table 1. Each line connecting dots, plus signs or asterisks corresponds to test stimulus luminances of 5, 10 or 25 cdm^{-2} respectively. The open squares represent the predictions of von Kries coefficient rule.

RESULTS

Figure 5a-c shows the experimental results and predictions according to von Kries proportionality rule. Connected data points display the variation of the chromaticity difference between test stimulus and the matched color (y-axis) as a function of the chromaticity difference between test field and test stimulus (x-axis). This difference is the measure of the shift in perceived color. It is obvious that there is a relation between the difference of test stimulus and test field on the one hand, and the variation in color shifts on the other hand. However, the results are somewhat difficult to interpret.

Both the magnitude of the shifts and the variation in induced color shifts are larger in the red (Figure 5a) and blue conditions (Figure 5c) than in the green condition (Figure 5b). Probably, this is the result of the fact that the distance in u',v' space between the average chromaticity of the green test field on the one hand, and the D65 reference field on the other hand, is smaller than the corresponding distances of the red and blue test fields (see Table 1 and Figure 2). Therefore, all the lines connecting the data points are quite flat in the green condition, whereas the general trend in the red and blue conditions is peaked.

In Figure 5a and 5c most of the lines illustrate two common features in the variation of the magnitude of color shifts. First, there is a peak representing the greatest color shift in most of the curves around a color distance between test stimulus and test field of 0.05 u',v' units, the peak being the least distinct in the case of a 25 cdm^{-2} target luminance. Second, beyond the color distance between the test stimulus and test field producing maximum color shifts, chromatic induction becomes small, and even approaches zero in the red condition at large u',v' distances.

Not only the chromaticity difference between test stimulus and test field has an effect on the magnitude of color shifts, the luminance of the test stimulus has an effect as well. It is obvious in all of the plots that as the luminance of the test stimulus increases, both the shift and its variation become smaller. The latter is especially true for 25 cdm^{-2} experiments.

If the experimental results are compared to the curves of von Kries' prediction, the difference becomes larger in the red and green conditions, and smaller in the blue condition.

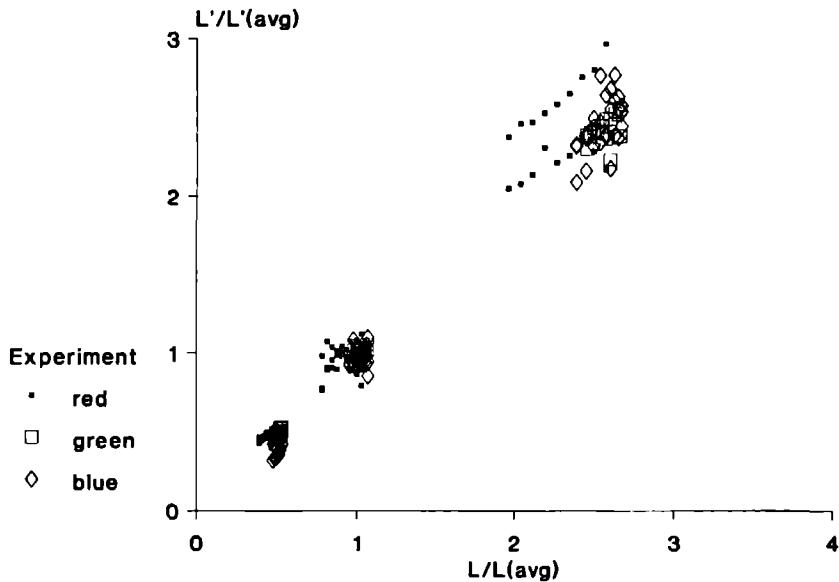
As the distance of target from its surround increases, the experimental curves go down, whereas the prediction curves, go up in the red and green conditions. In fact, the u' -coordinates of the two points at the right end of the prediction curve in the red condition become negative, which is beyond the u',v' -space. This suggests that von Kries' proportionality rule fails to predict data at the large distance between test stimulus and its surround under extreme levels of adaptation.

Compared to the red and green conditions, the difference between experiment and prediction for large differences between test field and test stimulus, is smaller in the blue condition. In the latter condition the prediction is close to the experimental results if the difference between test field and test stimulus is larger than 0.05 u',v' -units. However, in the left side of the blue condition plot, in which the color of test stimuli are more similar to its surround, the differences between experiment and prediction are larger.

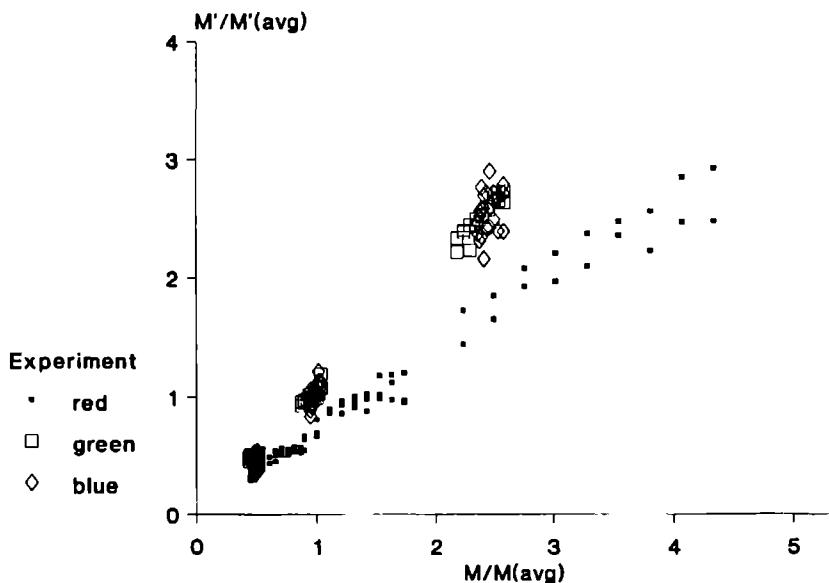
By transforming the experimental data from u',v' -chromaticities to cone system fundamental responses (see Appendix A), quantities corresponding to the retinal mechanisms underlying chromatic adaptation can be obtained. Next von Kries ratios (von Kries, 1905; see also Worthey & Brill, 1986), that are in fact ratios between a stimulus and the average of its surrounding fields, can be calculated (see Appendix B).

In Figure 6a-c the ratios of the test stimuli and the average of the surrounding test fields are plotted against the corresponding ratios of the matched colors with the D65 reference fields, for all levels of adaptation (red, green and blue). Inspection of the long wave system plot (Figure 6a) reveals three clusters of data points corresponding to the increasing von Kries ratios in the 5, 10, and 25 cdm^{-2} respectively. To a lesser extent this clustering is also found in the middle wave system plot (Figure 6b) but it is nearly absent in the short wave system plot. The clustering is due to the limited dynamic range to color differences of the L-wave and the M-wave systems. Large changes in chromaticity, as defined in u',v' -space (see Figure 3), do not produce large response ranges in the L-wave system and the M-wave system. The only exception is the M-wave response range in the red condition. This can be easily understood by inspection of Figure 7a-d.

L-system von Kries ratios



M-system von Kries ratios



S-system von Kries ratios

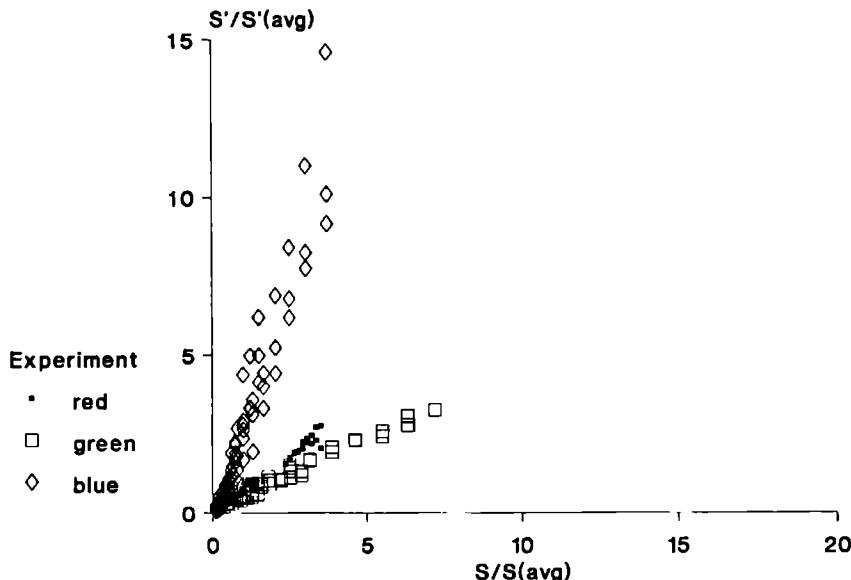


Figure 6. Ratios of match and average D65 reference field colors (quoted quantities on y-axis), against the corresponding ratios of test stimulus and average test field colors (x-axis) for the (a), L-, (b), M and, (c), S-wave sensitive receptor systems. Average colors of reference and test field are followed by "(AVG)".

In this plot the relative, von Kries adapted, receptor sensitivities are displayed. The maximal sensitivities in the D65 matching surround are set to 1.0 (Figure 7a). Figure 7b-d represent the sensitivities of the von Kries adapted eye in the red, green and blue conditions relative to those in the D65 matching surround. The S-wave system is the most sensitive, with a maximum von Kries coefficient in the green condition (nearly 2.5) and a minimum in the blue condition (around 0.25). The variation in the von Kries coefficients is much smaller for the M-wave and L-wave systems. All coefficients are around 1.0 except in the M-wave coefficient in the red condition (1.6). Because the average surround colors that were used in this study were close to the most extreme chromaticities that can be produced with our equipment, this implies that, taken over all surrounds, the S-wave system's responses are the most informative (see also Lucassen and Walraven, 1991).

Let's take a closer look at the S-wave system responses (Figure 6c), especially those obtained in the green condition and in the blue condition. If a linear regression line were plotted through these data points the slopes would seriously differ. The slope in the blue condition would be much larger than 1.0, while the slope of the green condition would be

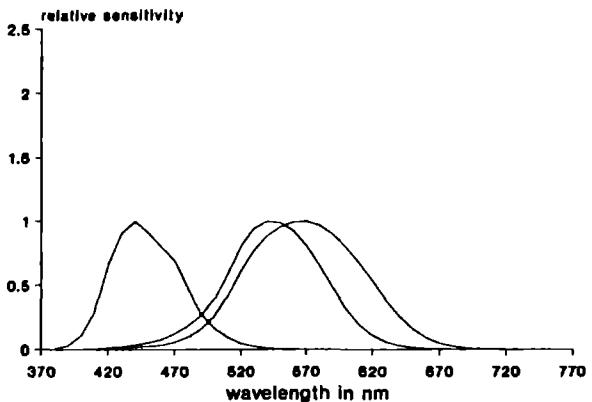
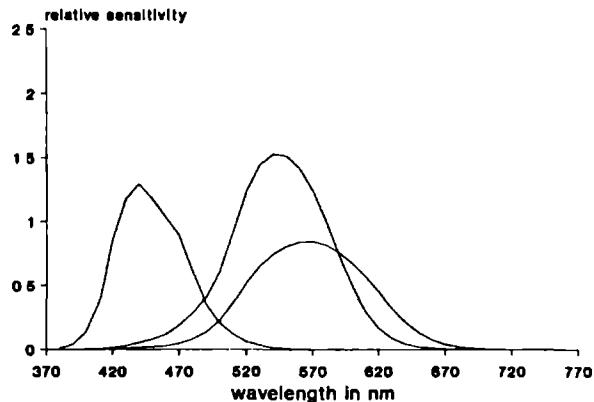
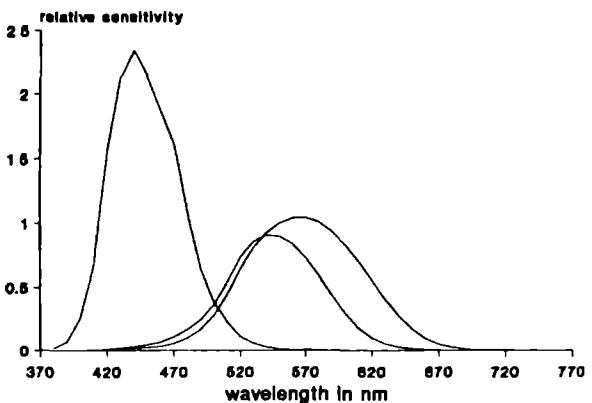
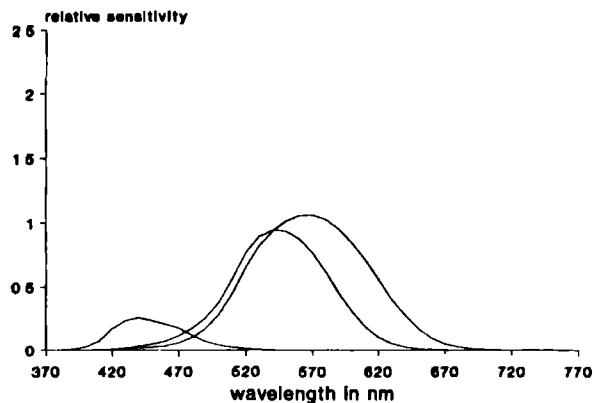
D65 reference field**Red test field****Green test field****Blue test field**

Figure 7. Relative spectral von Kries adapted sensitivities for the (a), D65 reference field, (b), red, (c), green and (d), blue test fields. The relative sensitivities for the D65 reference field have been set 1.0.

considerably lower than 1.0. This result can also be related to the relative, von Kries adapted, sensitivities of the S-wave system (see Figure 7). Decreased sensitivity (blue condition) corresponds to a slope larger than 1.0, while increased sensitivity (green condition) results in a slope smaller than 1.0.

In fact, the difference between the S-wave responses in the blue and green conditions is an extreme example of the fact that the von Kries adaptation model does not lead to straightforward predictions in an asymmetric matching task. In Figure 8 the results of the regression analyses performed on all conditions and for each separate cone system are displayed.

Ideally, one would like to treat the three cone systems identically because the processing characteristics of the systems may be assumed fundamentally equal, although the response ranges are quite different. Indeed, there is no theoretical objection to do so. However, methodologically this is not allowed because the values obtained for each of the three receptor systems are not independent, there is large overlap between the spectral sensitivities of the L- and M-cones for example (see Figure 7). Therefore the three cone systems were considered separately for each condition. Only if 1.0 slopes and 0.0

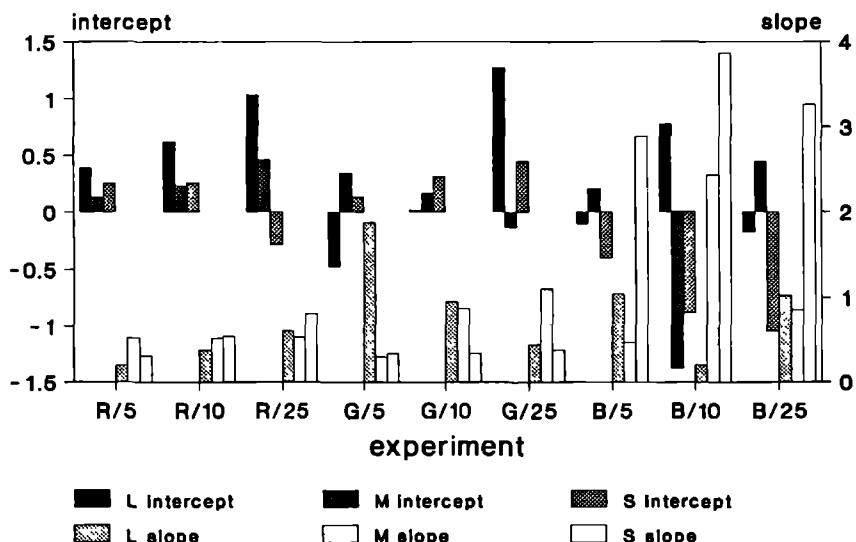


Figure 8. Experiment specific estimates of the intercepts (left y-axis) and slopes (right y-axis) of the fit of the data with the von Kries adaptation model. The nine different experiments are put on the x-axis. Each of the nine experiments has six estimates, three intercepts (left three bars) and three slopes (right three bars) for each of the (from left to right) L-, M- and S-wave sensitive receptor systems.

intercepts are estimated in all three regression equations simultaneously, one for each cone system, theoretical perfect predictors are obtained.

The most striking inconsistency has already been discussed above. Because of the limited response range of the cone systems in some conditions, it is difficult to draw any conclusions from these data. This holds especially for the L-wave and M-wave systems in the green and blue conditions. Nevertheless, it is obvious that there is much variation in the slopes and intercepts between the conditions and that adaptation is far from perfect in all conditions and for each cone system. One could argue that because of its simplicity, von Kries adaptation has to be considered as a global model for chromatic adaptation, but because of its globalness a lot of inconsistencies will show up if the data are inspected in more detail, as in Figure 8. Therefore we also performed a regression analysis on all data.

A general regression analysis was performed on the predictions of some other models for chromatic adaptation, other than the von Kries model. All of them are based on a normalizing operation and therefore they can be taken as modified versions of the von Kries coefficient rule. Our intention is to present an indication of the difference in performance of theoretically different adaptation models that incorporate von Kries coefficient rule in some version, without having the pretention of being complete. The nature of the modifications with respect to the coefficient is different, as are the reasons for the modifications. Land's Retinex Theory (Land, 1986a) was originally designed to deal with color constancy in object perception and is based on lightness rather than brightness. The model of Takahama, Sobagaki and Nayatani (1984) was modified to predict the effect of chromatic adaptation on object color, and Lucassen and Walraven's (1991) model was designed to describe both the contrast between stimulus and surrounding fields as well as absolute cone system responses. In all these models a contrast ratio of the stimulus with its surrounding fields is determined. Therefore we also looked at the Michelson contrast and the difference contrast. Additionally the log-transformation of the von Kries responses were considered to obtain lightness values. All computations are described in Appendix B.

In the analyses the model transformed values of the test stimuli served as predictors for the observed color matches. Next, the first order linear regression equations were solved. The estimates of the slopes and intercepts are displayed in Figure 9.

There are no dramatic differences between the models, the best predictions are obtained in the L-wave system, followed by the M-wave and S-wave systems for all models except one. The pure von Kries model, the Retinex Theory and the difference contrast are the

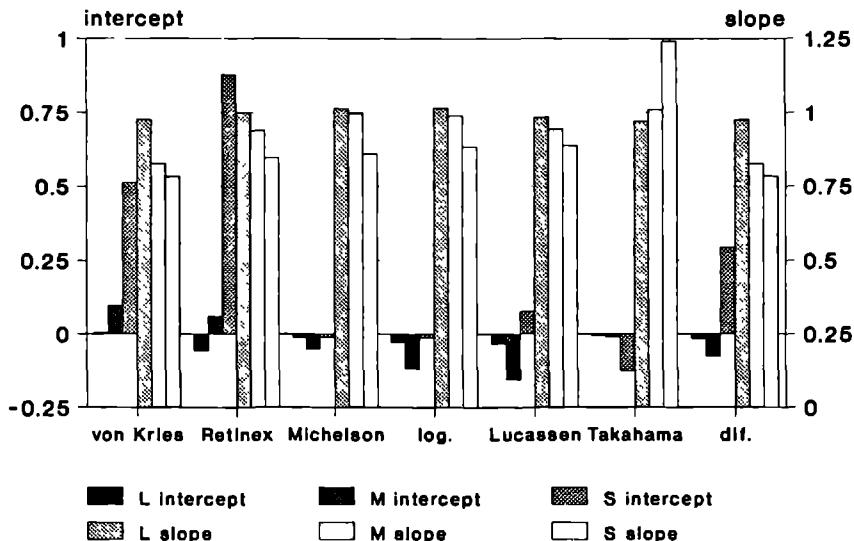


Figure 9. General estimates of the intercepts (left y-axis) and slopes (right y-axis) of the fit of all data with seven different models (x-axis). Three intercepts (left three bars) and three slopes (right three bars) for each of the (from left to right) L-, M- and S-wave sensitive receptor systems were estimated for each particular model.

least successful, mainly because of the large deviations from a perfect fit in the M-wave and S-wave systems. It is difficult to make a choice between the other four models that is based on these results. The advantage of the Michelson contrast and the log-transform of the von Kries ratio is that they are very simple compared to the models of Lucassen and Walraven, and Takahama et al. The latter two require additional fitting parameters to be estimated.

DISCUSSION

Comparing the experimental results to von Kries predictions in u', v' -space reveals a few interesting aspects. First, the systematic variation in the magnitude of color shifts due to the luminance of the target relative to its surround is consistent with the effect reported by Helson (1938). Helson found that the adaptation process is least effective for samples with a reflectance that is larger, and most effective for reflectances smaller than the adaptation reflectance, or average surround color.

Second, the lines connecting data points are peaked. The presence of peaks indicates that there is a range in which color shifts, as caused by chromatic adaptation, are maximal. As stated in the introduction we anticipated that the range of maximal color shifts would roughly correspond to the limited range of colors, lying around the average color, in the natural image. If this were true the maximal color shifts had to be found for test colors close to the average color of the surrounding fields, with a peak at a test stimulus/test field difference of 0.0 u' , v' -units. Therefore, it was unexpected to find maximum color shifts at test stimulus/test field differences of around 0.05 u' , v' -units (most prominently present in the red and blue conditions, see Figure 6). This deviation, however, is consistent with the chromatic induction data of Tiplitz Blackwell and Buchsbaum (1988). They also reported maximal effects for test colors that differed somewhat from the average color of the surround. At present we do not have an explanation for this peak shift but we may assume that it can not be a side effect of the binocular matching method. If this were the case then the peak shift had to be absent in Tiplitz Blackwell and Buchsbaum's data, because they did not use a binocular matching technique.

Because observed color differences are smaller than the predictions, the von Kries adaptation model consistently overestimates the resulting color shift. One remark concerning the blue condition has to be made. Whereas von Kries predictions get worse with increasing difference between test stimulus and test field in the red and green conditions, the predictions of the blue condition are more accurate for larger test stimulus/test field differences, although the predicted differences are always larger than the observed differences. This indicates that shifts along the yellow/blue dimension are more easily dealt with by the visual system as will be discussed below.

From figure 6a-d it followed that the activity in the S-wave system is the most informative if conditions with different adaptation levels are considered. Apparently, the human visual system has developed a higher sensitivity along the yellow/blue dimension. This can be easily understood from the fact that most illuminant changes under normal viewing conditions take place along the yellow/blue dimension (see Worthey, 1982, 1985). The phases of daylight for example mainly differ in yellowness or blueness. So, the dynamic range in the S-wave system's sensitivity is much larger than that of the M-wave and L-wave systems. Therefore the best demonstration of the inadequacy of von Kries color constancy is provided by the S-wave data. The imperfectionness is consistent with many other adaptation studies (e.g., Arend & Reeves, 1986; Breneman, 1987; Lucassen & Walraven, 1991; McCann, McKee & Taylor, 1976; Richards & Parks, 1971; Valberg & Lange-Malecki, 1990; Werner & Walraven, 1982; see also Chapter 3).

APPENDIX A

In order to obtain receptor responses, using Vos-Walraven primaries (Vos & Walraven, 1970) as tabulated by Vos (1978), a few intermediate conversions are required. First the u', v' -coordinates of the colors have to be transformed to x, y -coordinates,

$$x = 9u'/(6u' - 16v' + 12),$$
$$y = 4v'/(6u' - 16v' + 12).$$

Now Judd's (1951) modification of the x, y coordinates is applied to obtain x', y' -coordinates and luminance, Y' . This relation is given by

$$x' = (1.0271x - 0.00008y - 0.00009)/(0.03845x + 0.01496y + 1),$$
$$y' = (0.00376x + 1.0072y + 0.00009)/(0.03845x + 0.01496y + 1),$$
$$Y' = Y.$$

It should be noted that Y' does not exactly correspond to Y , however as long as stimuli are not in the extreme saturated blue region of the x, y -chromaticity diagram, the differences are negligible.

For a stimulus with chromaticity coordinates x', y' and luminance Y' , the tristimulus values are given by

$$X' = (x'/y')Y',$$
$$Y' = Y,$$
$$Z' = ((1-x'-y')/y')/Y'.$$

Following Vos (1978), L, M, S are given by

$$L = 0.1551646X' + 0.5430763Y' - 0.0370161Z',$$
$$M = -0.1551646X' + 0.4569237Y' + 0.0296946Z',$$
$$S = 0.0073215Z'.$$

APPENDIX B

Before presenting the transformations that were applied, a summary of the symbols used is given:

T	Cone response of the test stimulus
M	Cone response of the subject's match
f(q)	Transformation in which q represents either T or M
T _{Avg}	Average cone response of the test field
M _{Avg}	Average cone response of the reference field
a	Slope, to be estimated from the data
b	Intercept, to be estimated from the data

A perfect fit is expressed by a 1.0 slope and a 0.0 intercept.

von Kries coefficient rule

$$M = (M_{AVG}/T_{AVG})T$$

$$M/M_{AVG} = aT/T_{AVG} + b$$

Log-transform of von Kries adaptation

$$\log(M/M_{AVG}) = a \log(T/T_{AVG}) + b$$

Difference contrast

$$(M - M_{AVG})/M_{AVG} = a(T - T_{AVG})/T_{AVG} + b$$

Michelson contrast

$$(M - M_{AVG})/(M + M_{AVG}) = a(T - T_{AVG})/(T + T_{AVG}) + b$$

Lucassen and Walraven adaptation (1991)

$$f(q) = q^{0.33} \log(4.36q/q_{AVG})$$

$$f(M) = af(T) + b$$

Takahama, Sobagaki and Nayatani adaptation (1984)

Although this model was designed for object colors, we used it for CRT display colors. Originally, the computational scheme that is given below contained three quantities (i.e., luminous reflectance of a nonselective surround, p_0 , and illuminant chromaticity x, y) that are appropriate only for object colors. Therefore, we defined the average surround field

color to represent a nonselective surround for which the luminous reflectance was set to 0.1977 (corresponding to Munsell N 5/). Consequently, the original illuminant chromaticity x, y was replaced by the average surround field chromaticity x_{AVG}, y_{AVG} .

Instead of Vos-Walraven primaries, Pitt primaries are used to obtain predictions for this model,

$$\begin{aligned} R &= 0.07114X + 0.94940Y - 0.01562Z, \\ G &= -0.44617X + 1.31733Y + 0.09794Z, \\ B &= 0.91876Z. \end{aligned}$$

Although the general scheme is the same for each of the R, G, B channels, there are some differences in the coefficients, so a separate computational scheme is given for R, G and B ,

$$\begin{aligned} f(q_R) &= (q_R + 1)/(100\rho_0\xi + 1)p_r, \\ f(q_G) &= (q_G + 1)/(100\rho_0\eta + 1)p_g, \\ f(q_B) &= (q_B + 1)/(100\rho_0\zeta + 1)p_b, \end{aligned}$$

in which ρ_0 was set to 0.1977.

The quantities ξ, η , and ζ are given by

$$\begin{aligned} \xi &= (0.08676x_{AVG} + 0.96502y_{AVG} - 0.01562)/y_{AVG}, \\ \eta &= (-0.54410x_{AVG} + 1.21939y_{AVG} - 0.09794)/y_{AVG} \\ \zeta &= 0.91876(1 - x_{AVG} - y_{AVG})/AVG, \end{aligned}$$

where x_{AVG}, y_{AVG} represent the average chromaticity of the surrounding fields.

Finally the exponents p_r, p_g and p_b are defined as

$$\begin{aligned} p_r &= (6.469 + 6.362q_{R_{avg}}^{0.4495})/(6.469 + q_{R_{avg}}^{0.4495}) \\ p_g &= (6.469 + 6.362q_{G_{avg}}^{0.4495})/(6.469 + q_{G_{avg}}^{0.4495}) \\ p_b &= (8.414 + 8.091q_{B_{avg}}^{0.5128})/(8.414 + q_{B_{avg}}^{0.5128}) \end{aligned}$$

The regression model is defined by

$$f(M) = af(T)+b$$

Retinex Theory (Land, 1986a)

The first step is to transform cone system responses to lightnesses for which there are several theoretical and empirical candidates. Land (1986a) uses a log transformation of the cone inputs, the geometric mean taken across the scene represents the adaptation reflectance. We choose to use the relation described by Seim & Valberg (1986) that is in fact the reverse of the transformation of luminances, Y , to the Munsell Value scale, V (see Wyszecki & Stiles, 1967):

$$V(Y) = (Y-0.43)^{0.51}/((Y-0.43)^{0.51}+31.75), Y \geq 0.43$$

Because Y is a percentage of perfect white an illuminant level has to be defined. As the average color in a scene can be taken as a middle grey (Land, 1986a) this means that the average colors of the standard and test surrounds corresponds with Munsell paper N/5. Because a Munsell N 5/ has a reflectance of 0.1977 the estimate of the illuminant, I , can be found by increasing the average color with a factor of 1/0.1977.

$$\begin{aligned} I(x_{AVG}) &= (1/0.1977)x_{AVG} \\ f(x) &= V(100x/I(x_{AVG})) \\ f(M) &= af(T)+b \end{aligned}$$

CHAPTER 3

Color constancy is the phenomenon that the color appearance of objects is invariant notwithstanding variations in illumination. In real life situations, variations in illumination occur very often. For example, the spectral composition of daylight changes with the weather, the season and the time of the day. The artificial lights in our environment have many different spectral characteristics as well. In all these cases the visual system tends to perceive objects with constant colors.

Color constancy poses a problem because the object component and the illuminant component of the light that reaches the eye are not separately available to the observer. In recent attempts to model color constancy (e.g., Land, 1977, 1986a; Werner & Walraven, 1982; Grossberg & Todorović, 1988) the crucial question has often been put as: How does the visual system succeed in taking into account the variations in illumination? Because color constancy in these models is explained by an automatic elimination of the illuminant component by adaptation and lateral inhibition, these models represent sensory explanations. Color constancy models in artificial vision that try to recover reflectance and illuminant spectra (e.g., Dannemiller, 1989) also rely on automatic elimination of the illumination component (for a discussion of the relevance of these models to human perception see Jameson & Hurvich, 1989, and Troost & de Weert, 1991a). Traditionally there has been a controversy between sensory (Hering, 1874/1964; von Kries, 1905) and cognitive explanations (Helmholtz, 1867/1962; Katz, 1911/1935; Koffka, 1935) for color constancy (for a review see Beck, 1972).

Sensory explanations of color constancy are mechanistic, informational cues to the illuminant are not taken into account. It is implicitly assumed that the visual system does not even notice differences in illumination. On the other hand, cognitive explanations emphasize that both illuminant and object components need to be separately available somewhere in the visual system. In fact, the ability of subjects to make accurate estimations of illuminants (Beck, 1959, 1961) or the perception of illumination as separate from the object due to the figural organization of a scene (Gilchrist, 1980; Gilchrist, Delman & Jacobsen, 1983) may be considered as support for a more cognitive point of view.

¹ Troost, J., & De Weert, Ch. (1991b) *Perception & Psychophysics*, 50, 591-602.

For the sake of clarity, by *cognition* we refer to structural properties of the visual system that reveal the abstract perceptual organization of a scene, like implemented decision rules in pattern recognition (e.g., Leeuwenberg, 1982). We certainly do not mean conscious reasoning or willingness to see.

In this chapter it will be shown that neither purely sensory nor purely cognitive explanations provide satisfying descriptions of the phenomenon of color constancy (part I). Ideas from the research area of categorical perception will be used to formulate an alternative type of measurement of color constancy that incorporates both sensory and cognitive elements (part II).

PART I: SENSORY VERSUS COGNITIVE COLOR CONSTANCY

It is possible to create a sensory and a cognitive color constancy task with one and the same experimental setting by using different instructions. Contrary to sensory theories, cognitive theories emphasize the importance of separability, that is, separate perceptions of illuminant and object. In short, our theory is that if subjects are presented with an asymmetric matching task using a stimulus configuration that does not meet this separability by its figural organization, they will base their color matches solely relying on sensory information. In a cognitive task, additional information about the construction of the stimulus configuration can be given to subjects that enables an interpretation in terms of illuminants and real objects. In this case, matches will be affected by both sensory information and by the information about the separation of illuminant and object that is explicitly referred to.

Arend & Reeves (1986), using the procedure in which the illumination conditions were spatially separated, found an instruction effect. In this paper two replications of Arend & Reeves' instruction effect study will be reported. The first one, being a simultaneous asymmetric matching task in which subjects made adjustments of the achromatic locus, was an actual replication. The second one was a variant in the temporal domain - that is, a successive asymmetric matching experiment. The rationale behind the successive version of the experiment was 1) that it makes more sense to use situations in which one and the same object, or set of objects, are at one place at a time, and 2) that the light illuminating an object generally varies in time.

To test the effect of indirect cues to the illumination on color constancy matches, the subjects were given an instruction that forced them to extract indirect cues to the illuminant from the stimulus configuration. This condition will be called the *object-matching* condition. Because the illuminant itself was not visible these cues are referred to as indirect cues. The illuminant chromaticity was represented by the average color in the stimulus configurations. In the *exact-matching* condition, no reference to illuminants was made in the instruction.

To summarize, in the exact-matching condition color-constancy matches result from sensory processes only, since no additional information is given. In the object-appearance condition reference is made to illuminants and objects, so the matches are also supposed to be influenced by this separability.

EXPERIMENT 1A: Simultaneous matching

METHOD

Subjects

Fourteen subjects, all undergraduate students in psychology, with normal or corrected-to-normal vision and no color deficiencies, participated in this experiment for which they received course credits. They were naive as to the purpose of the experiment.

Equipment

Stimuli were presented on a high resolution (1280x1024 pixels) CRT monitor with RGB input connected to a Apollo DN4000 workstation. Chromaticity coordinates of the three phosphors were: R, $x = 0.618$, $y = 0.350$; G, $x = 0.280$, $y = 0.605$; B, $x = 0.152$, $y = 0.063$. It was possible to present 256 colors simultaneously. Each of the colors can have one of $256 \times 256 \times 256$ different RGB combinations.

In the matching experiment, the subjects could control the matching field by means of a mouse, whose position on an x,y -table corresponded with a point in the u,v -chromaticity diagram. The u,v -chromaticity diagram was chosen because it more accurately represents perceptual distances than does the x,y -chromaticity diagram (e.g., see Bartleson, 1980). The relation between x,y -chromaticity coordinates and u,v -chromaticity coordinates is given by

$$u = 4x/(-2x+12y+3)$$
$$v = 6y/(-2x+12y+3)$$

The CRT monitor was placed in a darkened room, (i.e., no light entered the room from outside and the walls had black wallpaper). The only light came from the CRT monitor. At a viewing distance of 90 cm the monitor screen subtended a visual angle of 24° in the horizontal direction and 19° in the vertical direction.

Stimuli

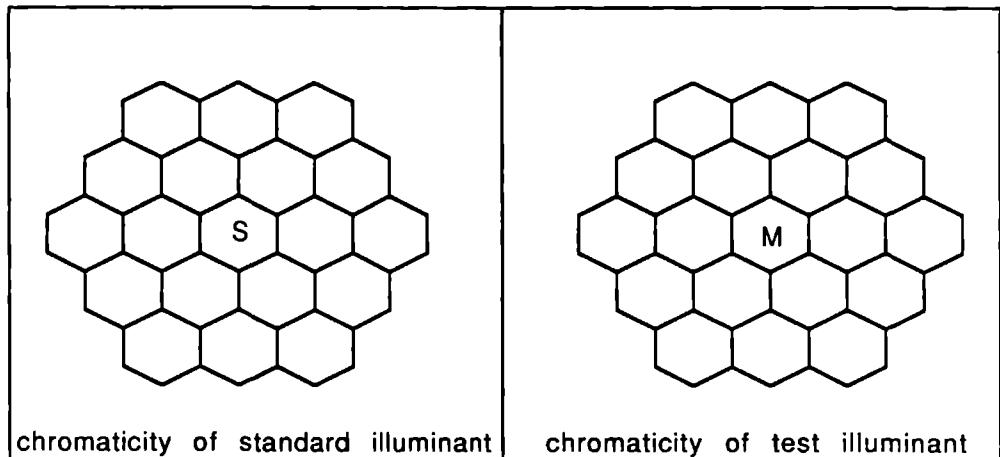


Figure 1. Stimulus used in the simultaneous-matching experiments. The left middle hexagon served as standard field (S); the right middle hexagon served as the matching field (M). The background chromaticities, as well as the average chromaticities of the surrounding hexagons, were equal to the standard illuminant chromaticity (left) and the test illuminant chromaticity (right). The subject could adjust the chromaticity of the match field on the CRT monitor with the aid of a mouse.

At a viewing distance of 90 cm, the subjects were presented two configurations of simulated patches against a neutral background. The left configuration was illuminated by the standard illuminant; the right configuration was illuminated by the test illuminant. The middle hexagons in the standard and test configurations served as the target and matching fields respectively (see Figure 1). The visual angle of one hexagon was 1.4° and 1.5° in the horizontal and vertical directions, respectively. Visual angles of the whole configuration of hexagons were 7° in the horizontal direction 6.3° in the vertical direction. The distance in visual angle between the two sets of hexagons was 9°. The colors in both configurations were simulations of the same set of papers under two different illuminants. Three illuminants making six different pairs were considered. Chromaticities of the

illuminants in u, v -coordinates were Illuminant 1, $u = 0.1977$, $v = 0.3123$; Illuminant 2, $u = 0.2161$, $v = 0.3239$; Illuminant 3, $u = 0.2354$, $v = 0.3363$. (To get an impression of possible chromaticities of daylight, see Table 1). The illuminant chromaticity was represented by the average color of the surrounding hexagons.

Table 1.

The u, v -Chromaticity Coordinates for Four Phases of Daylight

Corresponding Color Temperature (in degrees Kelvin)	u	v
4000 (sunlight)	0.224	0.337
6500 (overcast sky)	0.198	0.312
10000 (cloudy sky)	0.186	0.295
25000 (blue sky)	0.180	0.275

Note — The corresponding color temperature equals the temperature of a blackbody radiator having the same chromaticity as daylight.

The 18 different surrounding colors were equidistant (0.035 u, v -units) to the illuminant chromaticity under the first illuminant. This set of chromaticities was "von Kries transformed" to obtain corresponding chromaticities under the other illuminants (see Appendix). The average color of both the inner ring and the outer ring of hexagons was equal to the illuminant chromaticity. The average luminance of the surrounding colors was 7.5 cd/m² and the background luminance was set to 2.5 cd/m². Matches had to be made of the left target color at 10.0 cd/m². The chromaticity of the target was equal to the standard illuminant chromaticity.

Procedure

The subjects were made familiar with the response apparatus for 10 to 15 minutes. After this period, the subjects were instructed either to reproduce the left middle hexagon as precise as possible or to interpret the two configurations as real surfaces and to make an object match. In the object-match condition subjects received some brief general information about object colors and illuminants to demonstrate that the color of objects is partly determined by the light source. In fact, a light dimmer and some gray patches of paper were used for this purpose. An abbreviated version of the (written) object-appearance instruction is given below.

"What you see on the color display is a large sheet of grey paper. The patches in the left configuration are the same as the patches in the right configuration. The differences in color are caused by two different illuminants. Your task is to imagine what the target field will look like if you put it under the test illuminant. Adjust the color of the matching field accordingly."

In the second session subjects got the other instruction. In both conditions, the subjects were instructed to switch their gazes between the standard and the test configuration regularly for 1 to 2 sec. Each of the six illuminant pairs was presented 10 times, so 6x10 responses per subject were registered. If the subject was satisfied with an adjustment, he or she pushed a button, their response was registered; the next trial was given after 2500 msec. The order of the pairs of illuminants was random. In each trial, the starting chromaticity of the match field was randomly selected from the chromaticity diagram. Each session lasted about 1 h.

EXPERIMENT 1B: Successive matching

METHOD

Subjects

Eight undergraduate students in psychology, not the same as in Experiment 1A but all undergraduate students in psychology, with normal or corrected-to-normal vision and no color deficiencies, participated in Experiment 1B, for which they received course credits. None of these subjects had participated in Experiment 1A, and all were naive as to the purpose of the experiment.

Equipment

As in Experiment 1A.

Stimuli

At a viewing distance of 90 cm, the subjects were presented a standard configuration of simulated patches against a neutral background illuminated by the standard illuminant. Subsequently, the test configuration could be retrieved. In fact, this was the same configuration of simulated patches as in the standard, but now under the test illuminant. The colors in both configurations were simulations of the same surfaces under different illuminants. The middle hexagons in the standard and test configurations served as the

target and matching fields, respectively (see Figure 2). Visual angles of one hexagon and the whole set of hexagons were the same as in Experiment 1A.

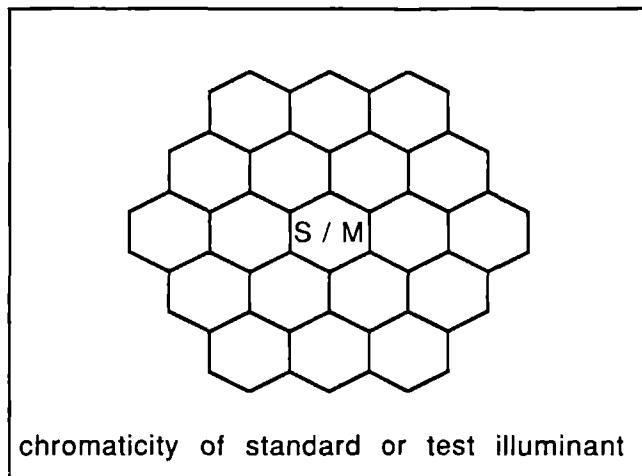


Figure 2 Stimulus used in the successive matching experiments. The middle hexagon served as either the standard (S) or the matching (M) field. The background chromaticity, as well as the average chromaticity of the surrounding hexagons, was equal to the standard illuminant chromaticity or the test illuminant chromaticity. The subject could adjust the chromaticity of the match field on the CRT monitor with the aid of a mouse.

The chromaticity of the standard illuminant was $u = 0.1973$, $v = 0.3139$. Chromaticities of the four test illuminants in u,v -coordinates were (1) $u = 0.2350$, $v = 0.3136$; (2) $u = 0.1595$, $v = 0.3143$; (3) $u = 0.1969$, $v = 0.3499$, (4) $u = 0.1972$, $v = 0.2784$. The illuminant chromaticity was represented by the average color of the surrounding hexagons, as was the background color. As in Experiment 1A, the 18 different surrounding colors were equidistant (0.035 u,v -units) to the illuminant chromaticity and the background luminance, average luminance of the surrounding colors and target luminance were set to 2.5, 7.5, and 10 cd/m², respectively. The set of chromaticities under the standard illuminant was "von Kries transformed" to obtain corresponding chromaticities under the other illuminants (see Appendix). The average color of both the inner ring and the outer ring of hexagons was equal to the illuminant chromaticity. The subjects only had to match the color. Five target colors were used. Their chromaticities were: (1) yellow, $u = 0.2072$, $v = 0.3526$; (2) red, $u = 0.2372$, $v = 0.3165$; (3) purple, $u = 0.2121$, $v = 0.2767$ (4) blue, $u = 0.1665$, $v = 0.2884$; (5) green, $u = 0.1635$, $v = 0.3353$.

Procedure

After a 10 to 15 minute period to familiarize themselves with the response apparatus, the subjects read the instruction from the screen. In the exact-matching condition, they had to reproduce the middle hexagon from the standard configuration as precise as possible in the test configuration.

In the simultaneous experiment, it became clear that the object matching condition was experienced much more difficult than the exact matching condition. Therefore, the object-matching condition was always presented in the second session in this experiment. After some brief general information about objects and illuminants, the experiment was started. The subjects had to interpret the two configurations as real surfaces. The object-matching instructions were the same as those used in the simultaneous-matching experiment.

In all, $5 \times 4 \times 3 = 60$ stimuli were given, five target colors, four test illuminants and three repeated measurements. Each trial started with the standard configuration containing one of the five target colors. These subjects were free to move their gaze over the screen. By pushing a button, the standard configuration disappeared and the background color of the test configuration was shown. After 1000 msec, the hexagons were displayed. In each trial, the starting chromaticity of the match field was randomly selected from the chromaticity diagram. By pushing the same button again, the subjects could switch between the two configurations; they were free to switch between the two configurations as much as they found necessary. Contrary to Experiment 1A no instructions were given about the duration of viewing one of the two configurations. After each switch between the standard and test configurations, the positions of the surrounding hexagons were changed randomly. This prevented the subjects from picking out a field with a color that resembled the target color in the standard configuration and then matching the color at the corresponding position exactly in the test configuration. If the subjects had finished their adjustment he or she pushed another button and the response was registered; the next trial was given after 2,500 msec. Each session lasted about 1 h.

RESULTS

First, an analysis of variance, using a within-subjects design, was performed on the distances between matched colors and target colors for the *u*- and *v*-chromaticity coordinates separately. A robust instruction effect was found in both the simultaneous and successive experiments for both dimensions [simultaneous experiment, $F(1,10) = 17.32$, $p < 0.01$, r^2

= 0.633 on the *u*-dimension and $F(1,10) = 7.72$, $p < 0.02$, $r^2 = 0.435$ on the *v*-dimension; successive experiment, $F(1,14) = 78.49$, $p < 0.001$, $r^2 = 0.849$ on the *u*-dimension and $F(1,14) = 103.20$, $p < 0.001$, $r^2 = 0.881$ on the *v*-dimension.

Because an analysis of variance is not informative about the degree of color constancy, we defined a two dimensional variant of the Brunswik ratio (Brunswik, 1928). The Brunswik ratio has often been used in brightness constancy and provides a measure of the degree of constancy. In the one-dimensional case it is defined as,

$$br = (O - S)/(E - S),$$

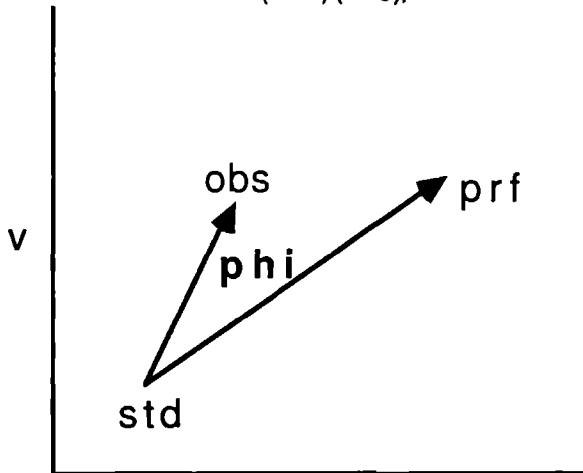


Figure 3. Graphical presentation of the parameter *phi*. *Phi* is defined as the angle between the line connecting the standard chromaticity (std) and the observed chromaticity (obs), and the line connecting the standard chromaticity and the perfect color-constancy match (prf). The angular deviation *phi* is defined in *u,v*-space.

where d_{obs} and d_{prf} are the euclidean distances between the location of the standard (u_{std}, v_{std}) and the observed match (u_{obs}, v_{obs}), and between the standard and the perfect color-constancy match (u_{prf}, v_{prf}) respectively. The Brunswik ratio is defined as the ratio of these distances. This measure is similar to the constancy index that was recently used by Arend, Reeves, Schirillo and Goldstein (1991), the only difference being that we took the distances from the standard, while they took distances from the perfect color-constancy match. Unfortunately, neither our Brunswik ratio nor Arend et al.'s constancy index gives complete information about the degree of color constancy. In the two-dimensional color-matching case an angular deviation must also be defined,

$$\begin{aligned}
U_1 &= U_{obs} - U_{std}, \\
V_1 &= V_{obs} - V_{std}, \\
U_2 &= U_{prf} - U_{std}, \\
V_2 &= V_{prf} - V_{std}, \\
\phi &= \text{sign}(U_1 V_2 - U_2 V_1) \arccos((U_1 U_2 + V_1 V_2) / (d_{obs} d_{prf})).
\end{aligned}$$

See Figure 3 for the graphical interpretation of the angular deviation ϕ .

Table 2

Means and standard deviations of br and ϕ (in degrees) values per condition and per illuminant pair of the simultaneous matching experiment. Standard deviations were calculated over subjects.

Condition	Illuminant	br		ϕ	
		mean	stdev	mean	stdev
Exact	12	0.53	0.07	-1	10
Exact	13	0.41	0.09	3	19
Exact	21	0.46	0.09	1	21
Exact	23	0.47	0.23	-3	28
Exact	31	0.42	0.10	2	19
Exact	32	0.48	0.11	4	10
Object	12	0.87	0.16	4	15
Object	13	0.79	0.18	4	13
Object	21	0.79	0.21	1	19
Object	23	0.90	0.17	7	16
Object	31	0.77	0.20	1	17
Object	32	0.81	0.25	-2	14

Table 3

Means and standard deviations of br and ϕ (in degrees) values per condition and per test illuminant of the successive matching experiment. Standard deviations were calculated over subjects.

Condition	Illuminant	br		ϕ	
		mean	stdev	mean	stdev
Exact	R	0.38	0.14	3	28
Exact	B	0.39	0.14	-1	19
Exact	G	0.41	0.37	7	25
Exact	Y	0.49	0.15	8	13
Object	R	1.51	0.52	4	16
Object	B	1.35	0.61	6	23
Object	G	1.29	0.41	-13	38
Object	Y	1.35	0.53	-7	21

In Tables 2 and 3, the *br* and *phi* are listed for the exact and object-matching conditions for Experiments 1A and 1B. For the exact-matching instruction the overall *br* and *phi* were found to be 0.46 and 0.9° in the simultaneous experiment and 0.41 and 4.4° in the successive experiment, whereas in the object matching condition of the simultaneous experiment *br* was 0.82 and *phi* was 2.4° and in the successive experiment *br* was 1.51 and *phi* was -4.7°. Perfect color constancy is achieved if *br* = 1 and *phi* = 0. So, if *phi* does not differ much from zero, as was the case in all experimental conditions, a *br* smaller than one indicates underconstancy, whereas a *br* larger than one indicates overconstancy. In Figure 4 the results of each experimental condition are displayed in polar coordinates.

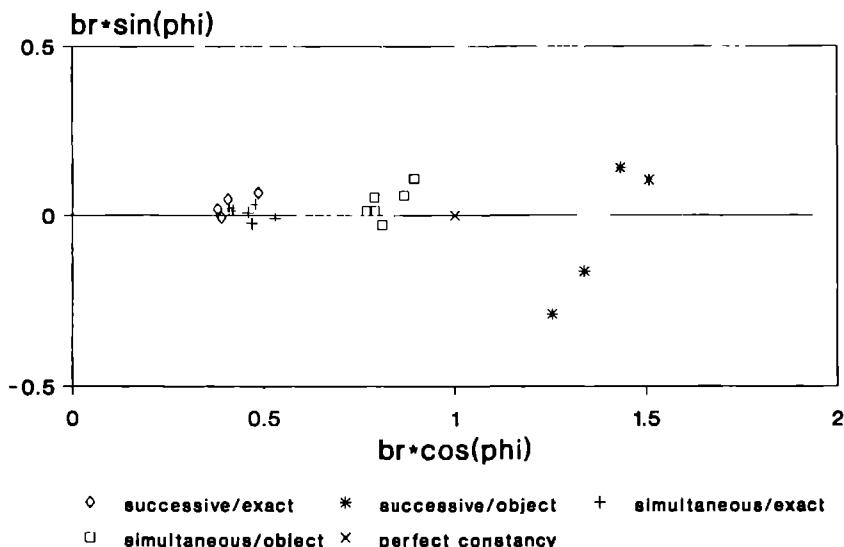


Figure 4. Plot of the data of the simultaneous- and successive-matching experiments in polar coordinates. Each symbol represents one illuminant level (note that there were six in the simultaneous experiment and four in the successive experiment). The length of the line drawn from the origin to a symbol is equal to the Brunswik ratio, *br*, in the corresponding condition, whereas the angle of this vector with the abscissa is equal to the angular deviation, *phi* (see also Tables 2 and 3).

All subjects saw color differences when comparing the standard with the test, and some of them reported they had difficulties with it. If color constancy was perfectly achieved by sensory processes only, color differences between standard and test configurations should not be perceived in either of the exact-matching or object-appearance condition. Similar to Arend and Reeves's (1986) results, the exact-matching condition revealed a relatively low degree of color constancy in both the simultaneous and successive experiments (simultaneous, $br = 0.46$, $\phi i = 0.9^\circ$; successive, $br = 0.41$, $\phi i = 4.4^\circ$). These findings may be considered as evidence for the view that color constancy is only partly determined by chromatic adaptation and lateral inhibition. Since no reference was made to the separation of illuminant and object components in the exact-matching condition, the degree of color constancy found in this condition is an estimation of the performance of sensory processes. However, because subjects freely switched between the standard and test configurations (although they were instructed to switch their gazes every 1-2 sec in the simultaneous-matching experiment), it is possible that the contribution of slow adaptation processes is underestimated. However, tasks such as these do not seem to activate all processes involved in the achievement of color constancy, they only incorporate chromatic induction.

The results of the object-appearance condition must be judged with care. Instead of matching *what one sees* (exact-matching) subject had to match *what they should see*. Therefore, these results do not point to a difference in sensation but rather to the ability of subjects to separate illuminant and object components and adjust their matches in accordance with their estimations. We think that because in the object-matching condition subjects strongly rely on indirect knowledge about objects and illuminants that had to be made explicit, the uncertainty of the matches is higher than in the exact-matching condition. Thus in our view, the differences in br between the object- and exact-matching conditions are caused by different judgements rather than different sensations. If this is the case, it is simply not allowed to relate these results to color constancy as a visual phenomenon only. One important remark must be made, however. The results of both the simultaneous- and the successive-object conditions suggest that knowledge about illuminant and objects can strongly influence color judgements; it does not imply that there are differences in sensory data between the two conditions.

A large overcompensation of the illuminant was found in the object-instruction condition of the successive experiment ($br = 1.51$, $\phi i = 4.7^\circ$). However, the shifts of the yellow and

green colors under the yellow test illuminant were difficult to accomplish because the resulting colors were very close to the borders of the color range of the monitor. Therefore, these data may be biased (if these colors are excluded, then average $br = 1.38$ and average $\phi_i = -2.0^\circ$). So far, we have not been able to formulate a satisfactory explanation for the fact that, in the object-instruction condition of the successive experiment, we found an overcompensation, whereas an undercompensation was found in the corresponding condition of the simultaneous experiment. This undercompensation, however, is consistent with Arend and Reeves's (1986) findings. One can speculate about the difference in procedure of presenting the standard and test illuminant (successive vs. simultaneous). In the successive task, subjects do not have a direct comparison of the illuminant, so any color matches are based on representations of the color they saw under the standard illuminant and the illuminant component itself. Color representations, or memory colors, are known to shift in time to prototypical colors that appear more saturated (e.g., Pijnenborgh, 1987). As a result of this shift, the illuminant component may be overestimated in the successive experiment.

To summarize, neither of the two conditions provides convincing color-constancy data. Contrary to the object-appearance condition, the exact-matching condition has the advantage of more closely registering the product of visual sensation. Unfortunately, it is confined to the sensory part of color constancy only. The advantage of the object appearance condition is that sensory information and the separation of illuminant and object components are integrated in the subjects' responses. If only the results are considered, the simultaneous-object-appearance condition, as opposed to the successive version, gives quite convincing evidence for color constancy. However, in the ideal case, one would like to have a color-constancy task that registers the product of visual perception in which the separation of illuminant and object components is met more naturally than is the case in matching tasks. For this purpose, we tried an alternative color-constancy task based on color naming.

PART II: CATEGORICAL COLOR CONSTANCY

The rationale for this proposal stems mainly from the next consideration. Usually, color constancy is described in a way that points to the ability of the visual system to eliminate the illuminant component from the light reaching the eye. It is a logical consequence that if color constancy is described as the result of a compensatory process, methods are used that can give detailed information about the success of such a process. Until now, the

matching method has been used most often because very accurate results about the degree of compensation can be obtained (as expressed, for example, by the Brunswik ratio that was described in the previous part I). In our view, the relatively low degree of color constancy reported in this paper (exact-matching conditions) and elsewhere (e.g., Arend & Reeves, 1986; Valberg & Lange-Malecki, 1990) implies the absence of appropriate compensatory mechanisms. However, unlike Valberg and Lange-Malecki (1990) we do not wish to conclude that color constancy is a non-existent phenomenon.

If color constancy would be described from a more natural perspective it can be argued that the purpose of color constancy is to prevent erroneous object-color perceptions due to variations in illumination. Color constancy would exist as long as an object is not assigned a different color under different illuminant conditions. Such a description does not deny compensatory mechanisms such as chromatic adaptation and lateral inhibition to be operative, but it poses less extreme demands on the performance of these processes. Or, as Jameson and Hurvich (1989, p.7) argue, color shifts resulting from different illuminations are not so great to prevent object identification by color, because these shifts remain within color category boundaries, which would not be the case without compensatory mechanisms such as chromatic adaptation and lateral inhibition. Recall that according to the common *discounting-the-illuminant* definition of color constancy, these mechanisms are implicitly supposed to perfectly eliminate the illuminant component from the light reaching the eye. From both the exact-matching data presented in the previous part and Arend and Reeves's data it appears that these mechanisms can only account for about 40% of the color shift necessary to reach a perfect color-constancy match. However, although these results seem to indicate that many errors are made in object-color perception, this is certainly not the impression one gets under ordinary viewing conditions: every object retains its color despite changes in illumination. If Jameson and Hurvich's suggestion about color-category boundaries is taken into account, the discrepancy between day life experience, on the one hand, and the relatively poor performance of chromatic adaptation and lateral inhibition processes, on the other hand, may very well be due to the categorical character of object-color perception. Although the visual system is very sensitive to color differences and can discriminate a very large number of colors, colors are perceptually grouped into discrete categories (e.g., Bornstein, 1987; Boynton, Fargo, Olson & Smallman, 1989; Uchikawa, Uchikawa & Boynton, 1989). Consequently, color constancy should be studied in an identification task rather than in a matching task which is more appropriate for discrimination phenomena. Harnad (1987) refers to identification tasks to specify tasks in which labels have to be

assigned to stimuli. So, applying the terminology of Harnad to the aforementioned description, color constancy should be studied as an identification phenomenon.

In Experiment 2 the subjects had to name the color of simulated object patches against a simulated neutral background under different illuminations. In this task, the success of identification - that is, assigning the same color name to the same patch under different illuminants - provides a measure of color constancy.

EXPERIMENT 2: Color naming

METHODS

Subjects

Thirty subjects, all undergraduate students in psychology, with normal or corrected-to-normal vision and no color deficiencies, participated as subjects in Experiment 2 for which they received course credits. They were naive as to the purpose of the experiment.

Equipment

The equipment in Experiment 2 was the same as that used in Experiment 1A, except that now the mouse was used to position a cursor on the CRT monitor.

Stimuli

At a viewing distance of 90 cm the subjects were shown a colored circle, subtending a visual angle of 1.6°. The basic color set contained 24 hue x 3 saturation x 2 luminance levels = 144 chromaticities of simulated patches, enabling us to investigate a wide range of colors. This set was chosen to represent a sufficiently large range of colors under the white illuminant (that approximated CIE illuminant D65). Next, the chromaticities of each of the 144 simulated patches was calculated according to the color shift due to the red, green, yellow and blue illuminants (see Figure 5). Thus, each of the 144 simulated patches could have five different chromaticities, depending on the illuminant.

The chromaticities of the illuminants were: white, $u = 0.1973$, $v = 0.3138$; red, $u = 0.2273$, $v = 0.3138$; green, $u = 0.1673$, $v = 0.3138$; yellow, $u = 0.1973$, $v = 0.3438$; blue, $u = 0.1973$, $v = 0.2828$. The chromaticity of the background corresponded to the chromaticity of the illuminants. The luminance of the background was 5 cd/m². The set of chromaticities under the standard illuminant was "von Kries transformed" to obtain corresponding chromaticities under the other illuminants (see Appendix). In the low and high luminance conditions, color stimuli were displayed at 2.5 and 10 cd/m² respectively. The three saturation

conditions differed in the distance of the colors to the achromatic locus of the white illuminant (0.02, 0.03 or 0.04 u,v -units).

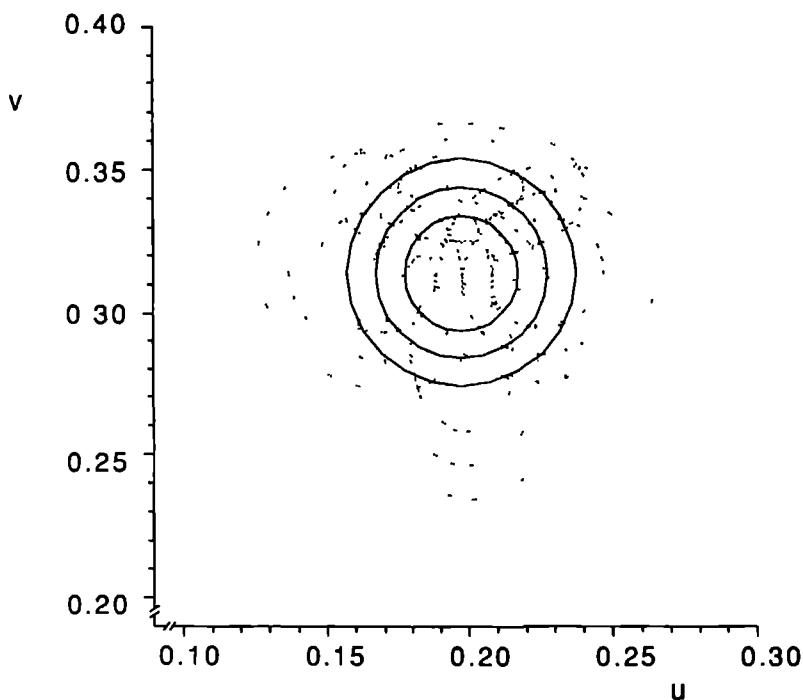


Figure 5. Stimulus set used in the color-naming experiment. On the solid lines, the chromaticities under the white illuminant are found. Each of the four other sets of three concentric ellipsoids (dashed lines) represent the colors under the test illuminants: (starting at the top and moving clockwise) yellow, red, blue, and green. The chromaticities of the simulated illuminants are located in the center of each set of ellipsoids.

Procedure

During the entire session, a response box, containing 12 different monolexemic color names was visible. The color of the lines of the response box and the characters was black. The subjects were instructed to carefully inspect the available response categories. The color names were in Dutch, so we give the English translations: red, green, yellow, blue, orange, pink, brown, white, grey, lilac and two words for purple (*paars* and *purper*).

which cannot be appropriately translated. The stimulus color was displayed for 750 msec. Next, the subjects had to place the cursor on 1 of the 12 color names and push a mouse button. The next trial followed after 500 msec.

Nothing was told about illuminants or objects. The subjects were simply instructed to choose the most appropriate color name. They were told not to wonder too long about their choices. Accuracy and speed were stressed, although it was mentioned that reaction times were not registered. No information about the response categories was given by the experimenter. The subjects were instructed to name the stimulus colors using their very own naming strategy.

After a few minutes of practice, the experiment started. In all 5×144 stimuli, divided over five blocks separated by a short pause, were presented to each of the 30 subjects. First, the color names under the white illuminant were obtained. Next, each of the four other illuminants was considered.

RESULTS

For each subject, the color name given to each simulated patch under a standard illuminant served as the standard color name. The standard illuminant was one of the five illuminants used in Experiment 2. Next, the standard color name was compared with each color name given to the corresponding simulated patch under one of the four other illuminants. The number of violations or deviations from the standard color name was counted. Thus, per simulated patch, the number of violations could range from zero to four, indicating perfect to imperfect identification over illuminants, respectively. For each subject 5×144 scores were obtained, 144 per standard illuminant. The categories for purple (*paars* and *purper*) and lilac were pooled in this analysis because a first inspection of the data revealed that they overlapped each other and were used interchangeably between and within subjects. The pooling had a marginal effect on the data.

Because our primary interest was to discover a general trend regardless of illuminant, or hue, saturation and luminance levels, all data were pooled. In Figure 6 (white bars), the proportional frequencies of the number of violations are displayed. As can be seen from this figure, the distribution of the number of violations is toward perfect identification (no violations occurred in 39.9% of all observations; 38.3% if the purple categories are not pooled). This general trend in the distribution of proportional frequencies was found in all

conditions. Therefore, color naming under different illuminations is an appropriate identification task to investigate color constancy.

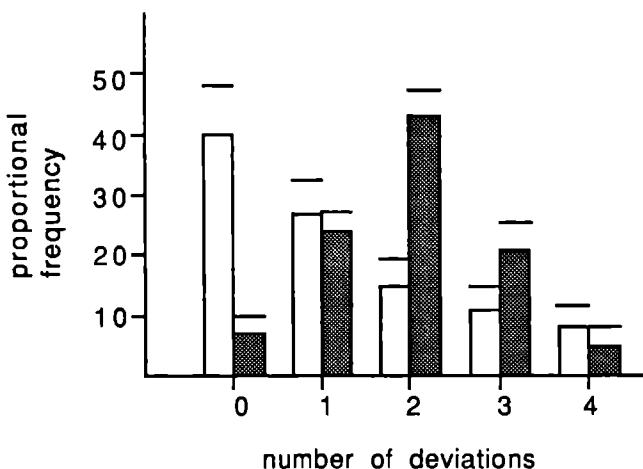


Figure 6. Proportional frequencies of the number of deviations that occurred in the color-constancy condition (white bars) and the control conditions (shaded bars) of the color naming experiment. Color names given under the standard illuminant were used as targets. So, under the four test illuminants, the total number of deviations per simulated patch could vary between zero (perfect identification) and four (no identification). Lines above bars indicate standard deviation.

Presumably, the size of the basic set of color names presented to the subjects affects the number of violations that are made. If subjects can choose only from four color names (e.g., red, green, yellow and blue), it is obvious that there generally will be more responses of the same name for a patch under different illuminations. Alternatively, increasing the set size may lead to a decrease of the degree of identification. Therefore, it is important to select the set of color names carefully. In this study, we used a slightly modified version of the color set that was empirically obtained by Uchikawa et al. (1989), who allowed their subjects to give any monolexemic color name that came in mind in response to colored patches. For the moment, we can only point to the set-size problem. Other experiments are in preparation to reveal in more detail the relations between set size and degree of identification.

It might be argued that the relatively high degree of identification is due to the fact that the area of chromaticities that are assigned one particular color name (e.g., red), may include many of the corresponding transformed chromaticities under other illuminants. So, if the transformed chromaticities of the patch called *red* fall in the area of all chromaticities called *red*, the response is not affected by the simulated illuminant. The high degree of identification would then be a result of an artifact, rather than a result of the separation of illuminant information present in the background. We anticipated this bias and included a control condition in the experiment. To estimate this bias, we also presented each of the 5 x 144 test chromaticities from Figure 5 against a background having the chromaticity of the white illuminant, rather than the corresponding illuminant chromaticity (located in the center of each of the five sets of three concentric ellipses in Figure 5). Thus, illuminant information was kept constant for all five sets of test chromaticities. Next, we obtained a second set of violations scores by applying the same procedure as described above to the control data. The results are also displayed in Figure 6 (shaded bars). The shape formed by the white bars differs substantially from the shape formed by the shaded bars. The peak of the constant illumination condition lies at two violations while for the experimental condition it is at zero violations. Therefore, the relatively high degree of identification cannot be ascribed to the fact that the area of chromaticities that are assigned one particular color name includes many of the corresponding transformed chromaticities under other illuminants.

To compare the results from the categorization experiment with those of matching experiments, a subsequent analysis was performed on the categorization data. In this analysis, the data were transformed to interval level in order to derive Brunswik ratios (Brunswik, 1928). The procedure to obtain Brunswik ratios from the data naming data will be described below. First, however, we want to emphasize that our only intention is to give an indication of the difference between naming and matching in general. We certainly do not want to demonstrate the superiority of one method over the other.

Because for each of the 144 simulated patches the subjects had to choose from a restricted set of 12 monolexemic color names, it was possible to locate each of these 12 color categories in the *u,v*-chromaticity diagram. All data were pooled over subjects. The locations were calculated by taking the average of the *u,v*-values of all color stimuli that were called red, green, purple, and so forth. This was done for the standard illuminant and for each of the four test illuminants; thus, five different maps of the location of color names in *u,v*-chromaticity space were obtained. It was then possible to calculate Brunswik ratios for each color name by following the same procedure as in Part I. The results are given in

Table 4. However, to obtain Brunswik ratios for each of the 144 simulated patches separately, a second transformation is required.

Table 4

Reconstructed means and standard deviations of *br* and *phi* (in degrees) values per monolexemic color category used in the color naming experiment. The results were averaged over all illuminant pairs (1 and 2: Dutch equivalents "paars" and "purper" respectively, see text).

Category	<i>br</i>		<i>phi</i>	
	mean	stdev	mean	stdev
Blue	0.75	0.09	-2	6
Brown	0.55	0.14	-13	14
Grey	0.33	0.14	7	45
Green	0.64	0.09	-5	8
Lilac	0.76	0.16	4	14
Orange	0.71	0.15	-9	15
Pink	0.79	0.05	-1	3
Purple1	0.84	0.24	0	10
Purple2	0.64	0.12	-4	9
Red	0.88	0.11	-3	8
White	0.36	0.13	-7	25
Yellow	0.60	0.09	-2	11

First, for each of the 5×144 chromaticities, the distribution of color-name responses was determined over subjects. Second, the relative frequencies under one illuminant served as weighting factors that were used to predict a response under another illuminant.

For example, under the red test illuminant a simulated patch is called *yellow* by 18 subjects, *orange* by 6 subjects and *red* by 6 subjects. The relative frequencies for *yellow*, *orange* and *red* are, 60%, 20% and 20% respectively. These numbers are used as weighting factors to predict a response under the green illuminant, for example, as follows. The *u,v*-coordinates are found by calculating the weighted average of the *u,v*-coordinates of the locations of *yellow*, *orange* and *red* in *u,v*-color space under the green test illuminant. It was then possible to calculate Brunswik ratios for each of the 144 simulated patches for every illuminant pair used in this experiment.

The *u,v*-coordinates of the standard, predicted and reconstructed observed colors can be substituted in the formulas for the two-dimensional Brunswik ratio given in Part I. The average *br* and *phi* for each illuminant pair are given in Table 5 and are displayed in Figure 7.

Table 5

Reconstructed means and standard deviations of *br* and *phi* values per illuminant pair in the color naming experiment. Standard deviations were calculated over the set of 144 simulated patches.

Illuminants	br		phi	
	mean	stdev	mean	stdev
WR	1.01	0.37	-23	21
WB	0.59	0.34	-34	56
WG	0.68	0.28	30	42
WY	1.22	0.23	7	24
RW	0.64	0.34	51	48
RB	0.46	0.27	-3	55
RG	0.58	0.25	14	22
RY	0.90	0.28	27	21
BW	1.08	0.35	12	24
BR	1.00	0.32	-5	12
BG	0.78	0.32	15	21
BY	1.02	0.17	5	13
GW	1.09	0.47	-27	28
GR	0.85	0.26	-17	14
GB	0.71	0.35	-37	28
GY	1.06	0.33	-10	19
YW	0.62	0.40	-53	78
YR	0.70	0.27	-38	32
YB	0.45	0.30	-27	39
YG	0.47	0.26	16	62

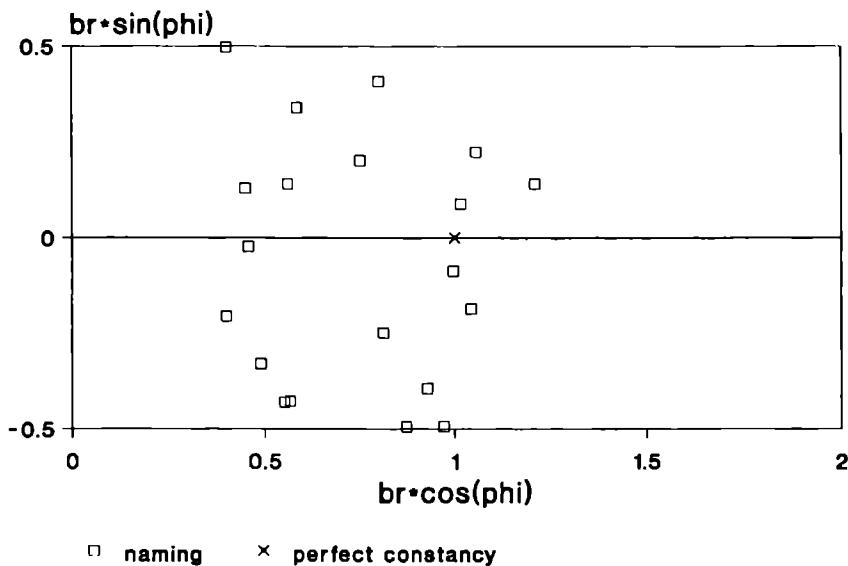


Figure 7. Plot of categorical Brunswik ratios, br , and angular deviations, ϕ , in polar coordinates. The length of the line drawn from the origin to a symbol is equal to br in the corresponding condition, whereas the angle of this vector with the abscissa is equal to ϕ . For transformations, see text. Each symbol represents an illuminant pair (see also Table 5).

DISCUSSION

Because in the matching experiment only the white illuminant was used as a standard in the matching experiment, only the entries in which the white illuminant is the standard are (see Table 5) are valid comparisons. If the white illuminant was used as a standard, the average br was 0.87 and ϕ was -5.2° . This is an improvement compared to the results of the exact matching experiment ($br = 0.41$, $\phi = 4.4^\circ$), although the variability of both br and ϕ is much larger in the naming experiment (see Table 5 and Figure 7).

Actually, a strict comparison between naming and matching is not possible because there are a few differences between the methods — the most important being the fact that a clockwise presentation of illuminant conditions was used in the naming experiment, whereas a randomly mixed presentation was used in the matching experiments. This point will be discussed in more detail below. Other differences were (1) free viewing was

possible in both matching experiments, whereas exposures of limited duration (750 msec) were used in the naming experiment; and (2) 18 different colors were presented in the surround in the matching experiments, whereas the only surround color was the one of the background in the matching experiments. Despite these differences, we think it is informative to present the transformation from categorical data to virtual matching data.

An explanation for the difference in average performance can be that the subject's state of adaptation was better controlled in the naming experiment because of the blockwise presentation of the illuminant conditions. Recall that, in the simultaneous-matching experiment, the subjects were instructed to switch their gaze from the one configuration to the other regularly for 1-2 sec. However, such an instruction does not guarantee that subjects in fact did so. In the successive-matching experiments, no restriction was imposed on the duration of viewing the standard and test configurations. One could argue that, in both matching tasks, the subject's state of adaptation was poorly controlled. In a sense, this is an inevitable artifact of the type of matching experiment in which both standard and test configurations are seen with the same eyes. A switch between standard and test configurations will always change the state of adaptation. Continuously modifying the color of the matching field requires the availability of the target color, whether it be simultaneously or successively, simply because matching takes time, and one wants to avoid distortions that may be addressed to memory. This means that a blockwise presentation of illuminant conditions, as in the naming experiment, is logically impossible. However, there is an alternative way to overcome this dissimilarity problem.

Although blockwise matching is impossible, a naming task in which the illuminant conditions are randomized from trial to trial is possible. Now, if one wishes to take an extreme stand and concludes that the difference between naming and exact matching is mainly determined by the different adaptational states, one would predict a considerable change in performance in the randomized condition. But this is not what happens. In Figure 8 the frequency distributions are plotted for a blockwise (white bars) and a randomized (shaded bars) presentation of illuminant conditions in a naming task that is similar to the one described above. Although the difference between the two distributions is in the direction that is expected from an adaptation explanation, it is clear that the difference is not serious.

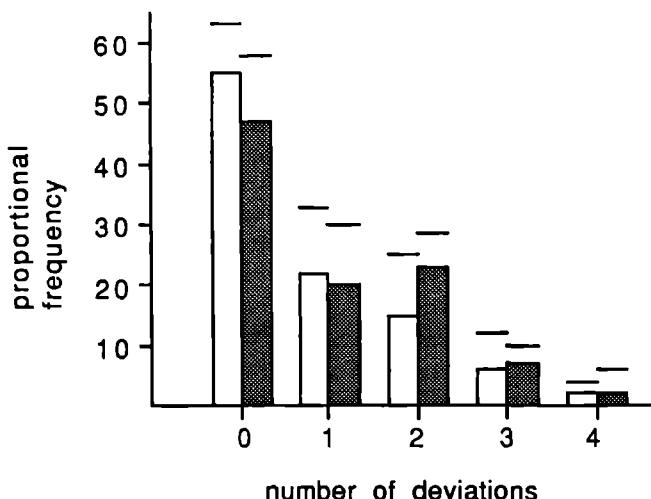


Figure 8. Proportional frequencies of the number of deviations that occurred in the blockwise (white bars) and the randomized illuminant (shaded bars) conditions of the additional color-naming experiment. Lines above bars indicate standard deviations. For explanation, see Figure 6.

CONCLUDING REMARKS

In this paper, an investigation of color-matching and color-naming tasks in the study of color constancy was reported. It was argued that color-matching tasks are not appropriate because these do not allude to the identification aspects of color constancy. Furthermore, it was found that unequivocal responses cannot be obtained using this kind of task because the type of instruction requires a fundamentally different interpretation of the data. As an alternative, a color-naming task was proposed. The number of violations in color naming under different illuminations appeared to be an appropriate measure of color constancy that does not require the separation of illuminants and objects to be explicitly made clear to the subjects.

Finally, we want to give a suggestion for the future study of color constancy. Following Koffka (1935), the separation of illuminant and object components is completely governed by an organizational process that can be thought of as a rule-based decision mechanism that is implemented in the hardware of the visual system. The activity of this mechanism

cannot be penetrated by cognitive reasoning, and its outputs are perceptually coercive, although they can be made available to consciousness. In our view, color constancy is not simply the result of an automatic elimination of the illuminant component in the light that reaches the eye, rather it is the product of a mechanism that prevents errors in the identification of objects due to differences in illumination. This new description of color constancy, in which the importance of stable object perceptions over illuminants is emphasized, requires approaches that model more complex and intelligent behavior than just adaptation and lateral inhibition. Although color categorization is not the solution to color constancy, the method of color naming is an appropriate tool that can be used in the investigation of the rules leading to a separation of illuminant and object components in visual perception.

All chromaticities under the test illuminants were calculated by applying a "von Kries transformation" to the chromaticities in the standard illuminant condition. We chose the von Kries method because we wanted to avoid the manipulation and construction of illuminant and reflectance spectra that are incorporated in models such as described by Dannemiller (1989) and van Trigt (1990). Specifically, by putting severe constraints on the infinite set of possible reflectance functions that give the same tristimulus values under a certain illuminant, i.e., metamerically reflectances, these models describe a one-to-one relation between tristimulus values and reflectance spectra for any specified illuminant spectrum. Because an illuminant spectrum is required as input, these models are restricted to make predictions under known illuminant spectra. Published tables (e.g., Bartleson, 1980; Wyszecki & Stiles, 1967) and methods to obtain these spectra (Judd, MacAdam & Wyszecki, 1964), cover only phases of daylight or artificial approximations of daylight, so another method is required if illuminants are more arbitrarily chosen (i.e., not restricted to represent daylight, as, for example, in this paper or in McCann, McKee & Taylor, 1976). The von Kries transformation is a method that makes good predictions; independent of the exact illuminant and reflectance spectra. Furthermore, it can be argued that the predictions of spectra models cannot be empirically discriminated from von Kries predictions (see Dannemiller, 1989, p.259).

To apply the von Kries transformation, each chromaticity under the standard illuminant had to be converted to receptor responses. In order to obtain receptor responses, using Vos-Walraven primaries (Vos & Walraven, 1970) as tabulated by Vos (1978), a number of intermediate conversions are required. First the *u,v*-coordinates of the target (or surround) colors have to be transformed to *x,y*-coordinates,

$$\begin{aligned}x &= 3u/(2u-8v+4), \\y &= 2v/(2u-8v+4).\end{aligned}$$

Judd's (1951) modification of the *x,y*-coordinates is applied to obtain *x',y'*-coordinates and luminance, *Y'*. This relation is given by,

$$\begin{aligned}x' &= (1.0271x-0.00008y-0.00009)/(0.03845x+0.01496y+1), \\y' &= (0.00376x+1.0072y+0.00764)/(0.03845x+0.01496y+1), \\Y' &= Y.\end{aligned}$$

It should be noted that Y' does not exactly correspond to Y , however as long as stimuli are not in the extreme saturated blue region of the x,y -chromaticity diagram, the differences are negligible.

For a stimulus with chromaticity coordinates x' , y' and luminance Y' , the tristimulus values are given by

$$\begin{aligned} X' &= (x'/y')Y', \\ Y' &= Y', \\ Z' &= ((1-x'-y')/y')/Y'. \end{aligned}$$

Following Vos (1978), R , G , B are given by

$$\begin{aligned} R &= 0.1551646X'+0.5430763Y'-0.0370161Z', \\ G &= 0.1551646X'+0.4569237Y'+0.0296946Z', \\ B &= 0.0073215Z'. \end{aligned}$$

Once receptor responses, R , G , B , of chromaticities of simulated patches under the standard illuminant are known, receptor responses R^* , G^* , B^* under one of the test illuminants can be derived by

$$\begin{aligned} R^* &= a_R R, \\ G^* &= a_G G, \\ B^* &= a_B B, \end{aligned}$$

in which von Kries coefficients a are given by,

$$\begin{aligned} a_R &= R^*_{REF}/R_{REF}, \\ a_G &= G^*_{REF}/G_{REF}, \\ a_B &= B^*_{REF}/B_{REF}. \end{aligned}$$

Where R_{REF} , G_{REF} , and B_{REF} stands for the standard illuminant and R^*_{REF} , G^*_{REF} , and B^*_{REF} for the test illuminants. Both illuminants are assumed to have the same energy. Unfortunately, the von Kries adaptation model does not describe how to obtain the references themselves. However, there is general agreement to take a spatial average (e.g., Brill & West, 1986; Land, 1986a). Results of empirical studies suggest that a spatially weighted average should be used (Reid & Shapley, 1988; Tiplitz Blackwell & Buchsbaum,

1988). In fact, this was the motivation to choose the average color of both inner and outer rings of surrounding hexagons in the matching experiments equal to the background color that had the chromaticity of the illuminant.

Once R^* , G^* , and B^* are obtained one can find the u,v -coordinates by applying the reverse procedure. First,

$$\begin{aligned}X' &= 2.94483R^*-3.50013G^*+29.08968B^*, \\Y' &= 1.00000R^*+1.00000G^*+1.00137B^*, \\Z' &= 136.6303B^*.\end{aligned}$$

Then from tristimulus values to chromaticity coordinates x' , y' and luminance, Y' ,

$$\begin{aligned}x' &= X'/(X'+Y'+Z'), \\y' &= Y'/(X'+Y'+Z'), \\Y' &= Y'.\end{aligned}$$

And to x,y and Y ,

$$\begin{aligned}x &= (1.00709x'+0.00008y'+0.00009)/(-0.03867x'-0.01537y'+1.03450), \\y &= (-0.00347x'+1.02710y'-0.00785)/(-0.03867x'-0.01537y'+1.03450), \\Y &= Y'.\end{aligned}$$

And finally from x,y -coordinates to u,v -coordinates with,

$$\begin{aligned}u &= 4x/(-2x+12y+3), \\v &= 6y/(-2x+12y+3).\end{aligned}$$

CHAPTER 4

TECHNIQUES FOR SIMULATING OBJECT COLOR UNDER CHANGING ILLUMINANT CONDITIONS ON ELECTRONIC DISPLAYS¹

The tristimulus specification of an object color is dependent on both the spectral power distribution of the light source and the surface reflectance of the object. Thus, even under normal circumstances, in which spectral characteristics of illuminants vary in time (e.g., daylight, fluorescent and incandescent light), one and the same object will have a large range of tristimulus specifications depending on the conditions of illumination. Contrary to the colorimetric specification of object color, the perceived object color seems to be rather independent of changes in illumination. That is, the color appearance of objects is nearly invariant notwithstanding considerable variations in illumination. This capacity of the visual system is known as the color constancy phenomenon, and has been an important subject of interest in color perception since the nineteenth century (Helmholtz, 1867/1962; Hering, 1874/1964). Several hypotheses and models have been deduced from demonstrations and empirical data since then, the most popular contribution being Land's Retinex Theory (Land, 1977, 1986a). Most of these experiments have been conducted with the aid of real objects and real light sources (Helson, 1938; McCann, McKee & Taylor, 1976), but recently methods have been introduced to simulate the effect of illuminants on object color dynamically on a visual display connected to a digital computer (Arend & Reeves, 1986; Tiplitz Blackwell & Buchsbaum, 1988; Troost & de Weert, 1991b; see chapter 3). Depending on the amount of information that is known about illuminants and objects, a number of computational schemes can be followed to predict the tristimulus specification of object color under changing illuminant conditions. In each of these schemes different quantities are defined to predict object color under illuminant changes. This paper primarily concentrates on the characteristics and performance of candidate algorithms designed to simulate objects and illuminants on such devices.

Color constancy research is mainly concerned with how the visual processing system succeeds in arriving at nearly invariant surface color while the tristimulus specification of the light reflected from the object to the eye varies with changing illuminant conditions. In fact, the visual system accomplishes an n (tristimulus specifications) to 1 (color percept) reduction. Of course, the set of n tristimulus specifications belonging to one object under n different illuminants has to be a consistent set, i.e., there must be a physically realisable object with a surface reflectance function that results in the set of n tristimulus values

¹ Troost, J., & de Weert, Ch. (in press). *Color Research and Application*.

when held under the set of n different illuminants respectively. Although this is a trivial requirement if experiments are conducted with real objects and light sources, it is a significant criterion for constructing stimulus sets that are to be used in object and illuminant simulations. This criterion becomes especially crucial when spectral distributions of the simulated light source and/or reflectance spectra of simulated objects, are unknown. In both fundamental human color constancy research and computer graphics research, incomplete information has often to be dealt with for a few reasons. Color constancy is only possible to the extent that illuminant changes affect tristimulus values systematically. Thus, how object tristimulus values change under an illuminant substitution is itself part of the color constancy problem. If the essential systematic nature of illuminant effects were known, it would be of interest to experiment with such systematic effects in simulation. However, to simulate objects in uncompromising detail, both a collection of colored objects and a spectrophotometer to measure their spectral reflectances are required, or tabulated spectral distributions of illuminants and objects have to be used. Unfortunately, the number of available tables is very limited, and one may lack the color chips or the instrumentation. In computer graphics research often only tristimulus specifications of objects are available (Borges, 1991; Rogers, 1985), or, one may wish to specify realistic objects by a small number of parameters.

It is obvious, that there is a need for explication and validation of techniques that can be used to simulate consistent changes in tristimulus specifications, but surprisingly no systematic empirical studies have been described in the literature so far.

In the first short section we review the calculation of some visual quantities when the required information is complete. We then describe the estimation of an object's spectral reflectance from its CIE 1931 X , Y , Z values and the spectral power distribution of the illuminant. Two types of models are presented: the Sällström-Buchsbaum model (e.g., Brill & West, 1986; Buchsbaum, 1980; Dannemiller, 1989; Maloney, 1986; Maloney & Wandell, 1986; Sällström, 1974) and the model developed by van Trigt (1990). Because the former model uses a set of three basis reflectance functions as input two versions have been implemented, one with Cohen's (1964) and one with Parkkinen, Hallikainen and Jaaskelainen's (1989) basis reflectance functions of Munsell papers. These versions are abbreviated to SBC and SBP, respectively, through this paper. The third part describes tristimulus computations of object colors under different illuminations, starting from an adaptational theory point of view: the von Kries approach, based on the behavior of receptor absorption functions (von Kries, 1905; Worthey & Brill, 1986). Apart from human receptor responses, L , M , S , von Kries's model will also be applied to two other types of tristimulus specifications, i.e., CIE 1931 X , Y , Z and R , G , B phosphor luminances.

If a surface reflectance function of an object and n spectral power distributions of the illuminant are known, n sets of tristimulus values X_i , Y_i and Z_i are simply given by,

$$\begin{aligned} X_i &= \int \bar{x}(\lambda)S(\lambda)L(\lambda)_i d\lambda \\ Y_i &= \int \bar{y}(\lambda)S(\lambda)L(\lambda)_i d\lambda \\ Z_i &= \int \bar{z}(\lambda)S(\lambda)L(\lambda)_i d\lambda \end{aligned} \quad (1)$$

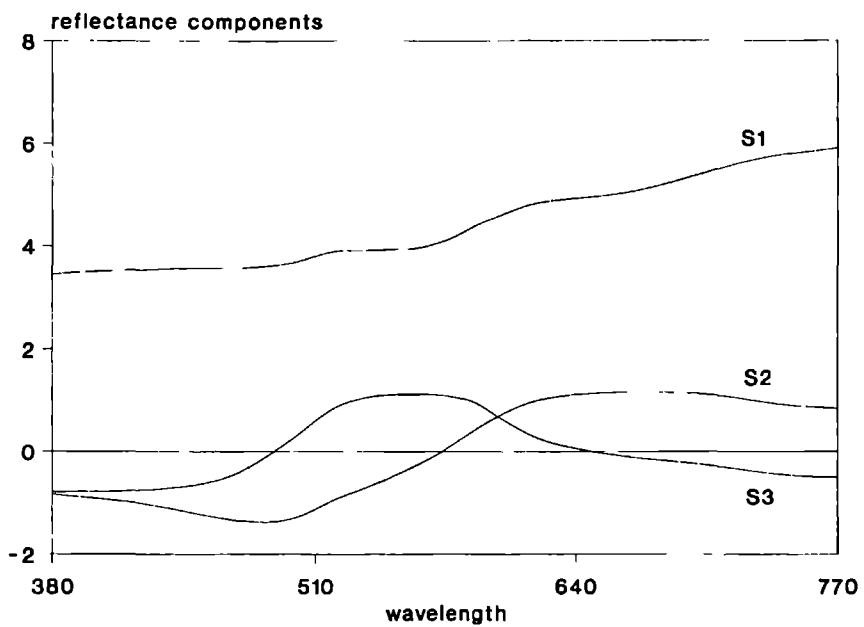
where x , y , and z are the CIE 1931 tristimulus functions, S is the surface reflectance and L_i denotes the spectral power distribution of the i -th illuminant. In this case complete information is available and the calculation can be performed without any additional assumptions. In practice, however, it is rather difficult to obtain illuminant, and specially reflectance spectra. Whereas a considerable number of illuminant spectra that represent phases of daylight, or artificial approximations of daylight, can be obtained from published tables (e.g., Bartleson, 1980; Wyszecki & Stiles, 1967), there are no extensive and systematic published collections of surface reflectance spectra. So, unless one wishes to restrict oneself to simulating only daylight spectra and the very few known surface reflectance functions, other techniques are required that can deal with incomplete information.

PREDICTING OBJECT COLOR WITH INCOMPLETE INFORMATION: (RE)CONSTRUCTING SURFACE REFLECTANCE FUNCTIONS

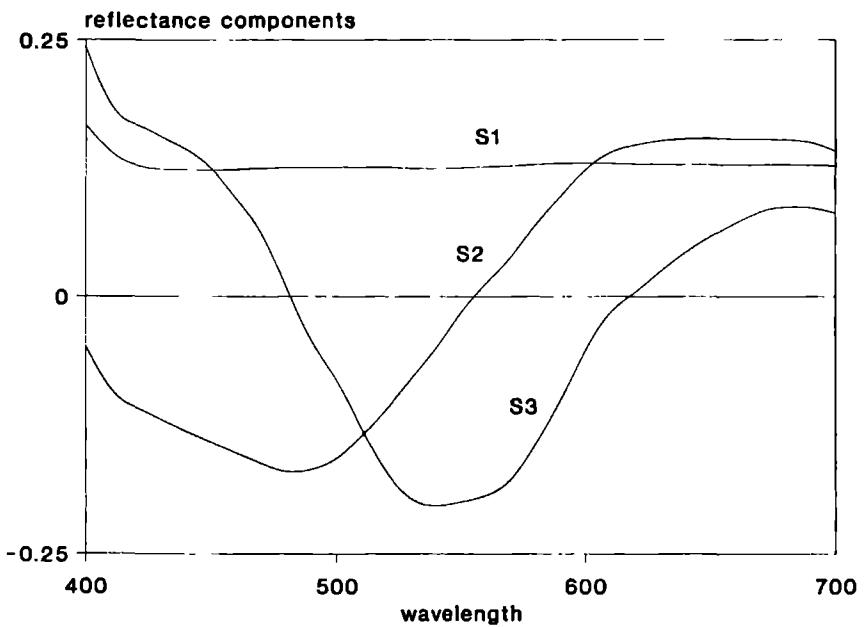
Cohen (1964) used the surface reflectance functions of 433 Munsell patches, performed a principal components analysis on the surface reflectance functions of 150 patches of this set, and found that the first three eigenvectors accounted for 99.18% of the variance. So, by a linear combination of only three basis vectors, surface reflectance functions of Munsell papers can be reconstructed with great accuracy. Formally,

$$S(\lambda) = \sum M_j S_j(\lambda), \quad (2)$$

in which M_j denotes the j -th scalar multiplier of the j -th basis vector S_j . Recently Parkkinen et al. (1989) applied a similar procedure to 1257 reflectance spectra of Munsell patches and published eight eigenvectors. Cohen's and Parkkinen et al.'s vectors are displayed in Figure 1a and 1b, respectively.



after Cohen (1964)



after Parkkinen et al. (1989)

Figure 1. First three principal components found by Cohen 19 (a) and Parkkinen et al. 20 (b). A large number of reflectance spectra can be reconstructed by linearly combining these basis vectors.

Although it has been suggested that this result can be taken as an explanation for the trichromatic nature of human color vision (Cohen, 1964; Dannemiller, 1989), we do not want to go into such speculations. In our view the apparent three dimensionality of the surface reflectance functions of Munsell papers is only a fortunate coincidence because it enables to reconstruct reflectances from tristimulus specifications (Troost & de Weert, 1991a; see chapter 5). In order to obtain a solvable set of linear equations we only used the first three eigenvectors of Cohen and Parkkinen et al. (see below). By applying the Sällström-Buchsbaum model to the first three vectors of Cohen (abbreviated to SBC) or Parkkinen et al. (1989) (abbreviated to SBP), it is possible to reconstruct the reflectance spectra of a large number of Munsell papers. Both the SBC and SBP model take tristimulus values of a Munsell paper, the corresponding set of basis vectors and a spectral power distribution of an illuminant as input, and give the surface reflectance spectrum of the Munsell paper under consideration as output.

By solving three linear equations the scalar multipliers M_i can be obtained. Substituting equation (2) in (1) and writing the result in matrix notation gives

$$\begin{bmatrix} X_I \\ Y_I \\ Z_I \end{bmatrix} = \begin{bmatrix} \int \bar{x}(\lambda)S(\lambda)_1L(\lambda)d\lambda & \int \bar{x}(\lambda)S(\lambda)_2L(\lambda)d\lambda & \int \bar{x}(\lambda)S(\lambda)_3L(\lambda)d\lambda \\ \int \bar{y}(\lambda)S(\lambda)_1L(\lambda)d\lambda & \int \bar{y}(\lambda)S(\lambda)_2L(\lambda)d\lambda & \int \bar{y}(\lambda)S(\lambda)_3L(\lambda)d\lambda \\ \int \bar{z}(\lambda)S(\lambda)_1L(\lambda)d\lambda & \int \bar{z}(\lambda)S(\lambda)_2L(\lambda)d\lambda & \int \bar{z}(\lambda)S(\lambda)_3L(\lambda)d\lambda \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} \quad (3)$$

or more briefly

$$p = FM, \quad (4)$$

where p is the 3×1 vector of tristimulus values, F is the 3×3 reflectance matrix and M is the 3×1 vector of multipliers that are needed to reconstruct the reflectance spectrum of the Munsell paper under consideration. Provided that both the vector of tristimulus values of a Munsell paper and the reflectance matrix are known, the vector of multipliers can be obtained by

$$M = F^{-1}p, \quad (5)$$

Wyszecki and Stiles (1967) published CIE 1931 chromaticity coordinates x, y and luminous reflectance, Y , of the recommended Munsell notations for 40 hues and 9 values at every second chroma step from two to the loci of optimal colors under CIE standard illuminant C, in total more than 2700. The transformation from x, y, Y to X, Y, Z is given by

$$\begin{aligned} X &= (x/y)Y, \\ Y &= Y, \\ Z &= ((1-x-y)/y)Y. \end{aligned} \tag{6}$$

So, by entering these data in the SBC or SBP model it is possible to obtain reflectance spectra of a large number of Munsell papers that cover a considerable part of the CIE 1931 x, y -chromaticity diagram.

Recently van Trigt developed a model that creates reflectance spectra for any set of tristimulus values as defined under any illuminant without any reference to real objects (Van Trigt, 1990). Van Trigt formulated three mathematical restrictions that are to be met, 1) $S(\lambda)$ under $L(\lambda)$ must be a solution of the color equations (see equation 1), 2) $S(\lambda)$ is comprised between zero and unity, $0 \leq S(\lambda) \leq 1$, 3) $S(\lambda)$ is the smoothest in the sense that $\int (dS/d\lambda)^2 d\lambda = \text{a minimum}$. So, whereas the SBC and SBP models produce spectra of Munsell papers, van Trigt's model generates the mathematically most smooth, but not necessarily physically existing, reflectance functions. Van Trigt's contribution can be considered as a mathematical excursion that is of special interest for color rendering purposes. Unfortunately, a detailed description of van Trigt's model is beyond the scope of this paper, but van Trigt reflectance spectra will be included in the simulations that will be described below. First, however, we will discuss the prediction of tristimulus values when either illuminant or reflectance spectra are unknown, and can not be reconstructed either.

PREDICTING OBJECT COLOR WITH INCOMPLETE INFORMATION: TAKING TRISTIMULUS RATIOS

If an illuminant spectrum is missing, and only tristimulus values are available, it is difficult to make predictions with the computational schemes from the previous sections. The method described by Brill and West (1986) is one candidate, but is based on the unfavourable assumption of a priori knowledge of three reference reflectances (Troost & de

Weert, 1991a). There is, however, another method that is based on von Kries' model for chromatic adaptation (von Kries, 1905; Worthey & Brill, 1986). By applying von Kries proportionality rule an illuminant invariant quantity is defined that relates the receptor responses of an object color in a scene, L , M , S , to the receptor responses of the illuminant of the scene under consideration L_{ILM} , M_{ILM} , S_{ILM} , simply by taking ratios (see Appendix, equations A1-A3). Once receptor responses, L , M , S , of chromaticities of simulated patches under the standard illuminant are known, receptor responses L^* , M^* , S^* under one of the test illuminants can be derived by

$$\begin{aligned} L^* &= a_L L, \\ M^* &= a_M M, \\ S^* &= a_S S. \end{aligned} \quad (7)$$

in which von Kries coefficients a are given by

$$\begin{aligned} a_L &= L_{ILM}^*/L_{ILM}, \\ a_M &= M_{ILM}^*/M_{ILM}, \\ a_S &= S_{ILM}^*/S_{ILM}. \end{aligned} \quad (8)$$

Where L_{ILM} , M_{ILM} , and S_{ILM} stand for the standard illuminant and L_{ILM}^* , M_{ILM}^* , and S_{ILM}^* for the test illuminant. Once L^* , M^* , and S^* are obtained one can find the x,y -coordinates and luminance, Y , by applying the reverse procedure (see Appendix, equations A4-A6).

If the illuminant is completely unknown, i.e., even tristimulus values are not available, the average color in a scene can be used as an estimator for the illuminant chromaticity at 50% intensity (e.g., Brill & West, 1986; Dannemiller, 1989; Helson, 1938; Judd, 1940; Land, 1986). The von Kries method avoids the manipulation and construction of illuminant and reflectance spectra that is incorporated in models such as described in the previous section. Because, published tables and methods to obtain these spectra only cover phases of daylight or artificial approximations of daylight, another method is required if illuminants are more arbitrarily chosen, i.e., not restricted to represent daylight (Lucassen & Walraven, 1991; McCann et al., 1976; Troost & de Weert, 1991b; Valberg & Lange-Malecki, 1990; see chapter 3). As will be shown in the next sections, the von Kries transformation is a method that makes acceptable predictions independent of the exact illuminant and reflectance spectra.

Making von Kries illuminant invariant quantities, Q , explicit (by substituting equation 8 in equation 7 and rearranging terms, see below), is useful to reveal the difference of the von Kries method with the methods described in the previous sections. Q_L , Q_M and Q_S , that are in fact integrated reflectances (Land, 1977, 1986a), are defined in the respective wavebands of the receptor sensitivity functions L , M , and S by

$$\begin{aligned} Q_L &= L^*/L_{ILM}^* = L/L_{ILM}, \\ Q_M &= M^*/M_{ILM}^* = M/M_{ILM}, \\ Q_S &= S^*/S_{ILM}^* = S/S_{ILM}. \end{aligned} \quad (9)$$

As was shown elsewhere (West & Brill, 1982; Worthey, 1985; Worthey & Brill, 1986) the width and the degree of overlap between the three respective wavebands, L , M , S , affect the accuracy of the von Kries method. In this study the question, however, is one concerning robustness, that is, what is the error of the von Kries predictions when they are compared to the predictions made with the SBC model, for example? Although very recently Borges (1991) mathematically derived a measure for this type of error, there have not been any studies addressing the empirical discrimination of the different methods that are available to predict object color under changing illuminations, so far.

SIMULATING OBJECT COLOR

Apparatus

All simulations were performed on a HP/Apollo 433 workstation with a 68030 processor and mathematical co-processor running under UNIX (version BSD4.3). Clock frequency and available working memory are 25MHz and 16Mb respectively. The phosphor chromaticities of the color monitor connected to the workstation, as supplied by the manufacturer, are $(x_R, y_R) = (0.618, 0.350)$, $(x_G, y_G) = (0.280, 0.605)$, $(x_B, y_B) = (0.152, 0.063)$.

Illuminants

Because the SBC, SBP and van Trigt models need a known illuminant spectrum, we used 9 phases of daylight (between 4000K and 20000K) in all simulations. Daylight spectra were obtained with the method of Judd, MacAdam and Wyszecki (1964; see also Wyszecki & Stiles, 1967) (equations 10-13) that takes color temperature as input and, after a few intermediate calculations, gives an illuminant spectrum as output (see Figures 2 and 3).

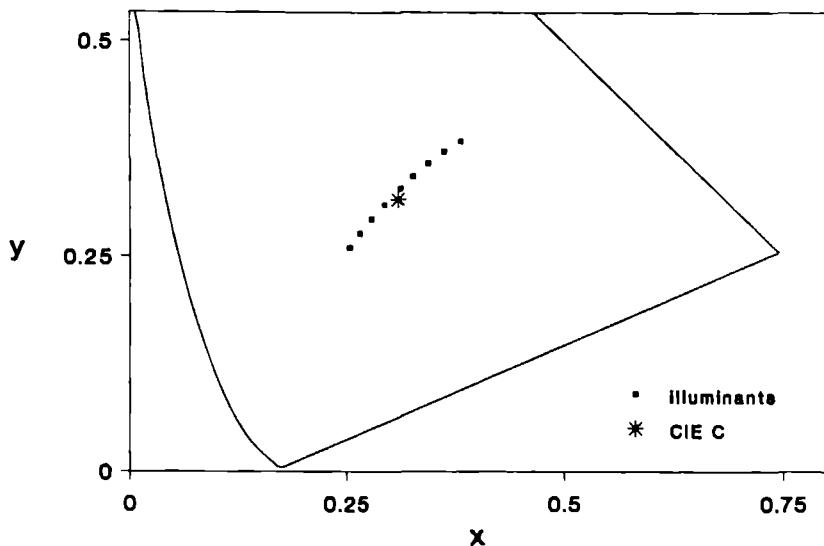


Figure 2. CIE 1931 x,y -chromaticity coordinates of the illuminants used in the simulations.

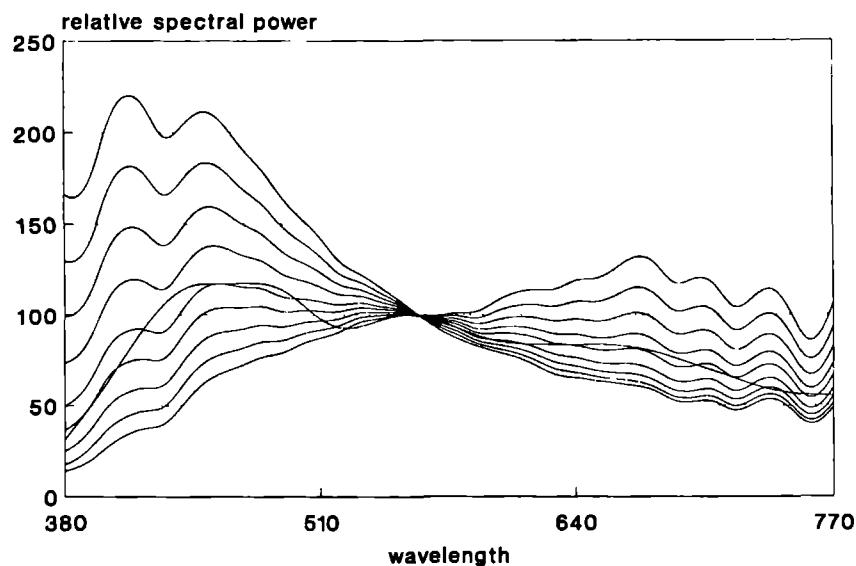


Figure 3. Relative spectral power distribution of the illuminants used in the simulations. Spectra are normalized to 100 at 560nm. The spectrum that crosses several spectra belongs to CIE standard illuminant C. All other spectra were generated by the method of Judd et al.

First, the relation between correlated color temperature of daylight, T , and the corresponding x chromaticity coordinate is given by

$$x = -4.6070(10^9/T^3) + 2.9678(10^6/T^2) + 0.09911(10^3/T) + 0.244063, \quad (10a)$$

for $4000K \leq T \leq 7000K$, and

$$x = -2.0064(10^9/T^3) + 1.9018(10^6/T^2) + 0.24748(10^3/T) + 0.237040, \quad (10b)$$

for $7000K \leq T \leq 25000K$. Next the x,y -chromaticity coordinates of daylight satisfy the relation

$$y = -3.000x^2 + 2.870x - 0.275, \quad (11)$$

with x within the range 0.250 to 0.380. For the von Kries model these x,y -coordinates, and arbitrarily chosen luminance, Y , provide enough information to represent the illuminant (calculate L_{ILM} , M_{ILM} , S_{ILM} with equations A1-A3). However, for the spectra models the spectral power distribution of the illuminant has to be calculated first.

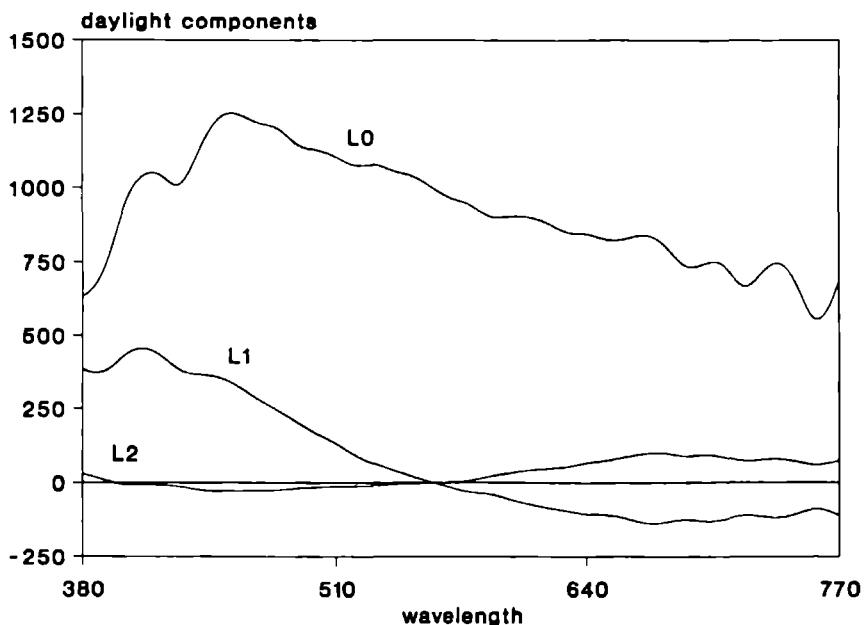


Figure 4. Mean spectral irradiance distribution of daylight, $L(\lambda)_0$, and first and second eigenvectors, $L(\lambda)_1$ and $L(\lambda)_2$ of daylight spectra.

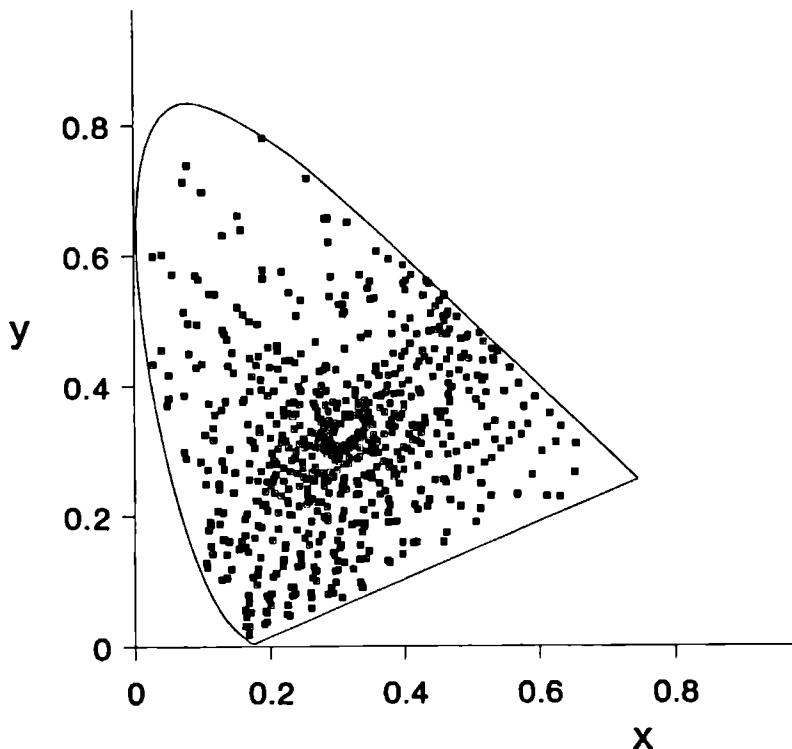
Once x, y -coordinates are known it is possible to calculate the spectral power distribution with correlated color temperature T . Judd et al. (1964) showed that a large number of phases of daylight can be described by a linear combination of only three basis functions (see Figure 4), the first one being the mean spectral irradiance distribution of daylight, $L(\lambda)_0$, the other two the first and second eigenvectors, $L(\lambda)_1$, and $L(\lambda)_2$.

The reconstructed spectrum is of the form

$$L(\lambda) = L(\lambda)_0 + \mu_1 L(\lambda)_1 + \mu_2 L(\lambda)_2. \quad (12)$$

For the particular case of daylight the scalar multipliers μ_1 and μ_2 are obtained from

$$\begin{aligned} \mu_1 &= (-1.35151.7703x + 5.9114y)/(0.0241+0.2562x-0.7341y), \\ \mu_2 &= (0.0300-31.4424x+30.0717y)/(0.0241+0.2562x-0.7341y). \end{aligned} \quad (13)$$



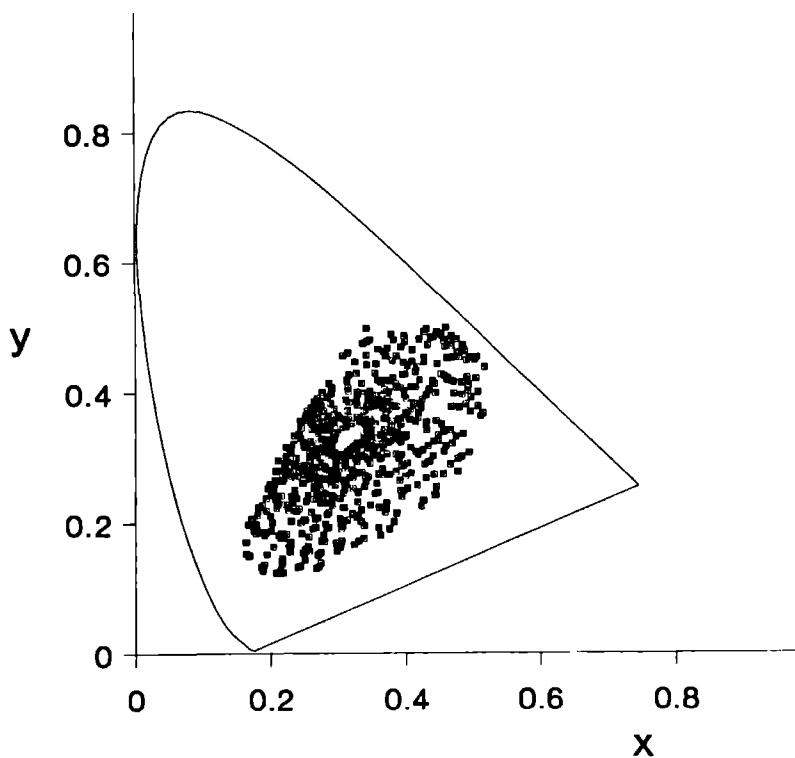


Figure 5. CIE 1931 x,y -chromaticities of the patches, as under CIE standard illuminant C, in the unrestricted (a) and restricted (b) stimulus set. (To improve the legibility of the plots, only every fourth patch is displayed).

Objects

We used simulated Munsell papers as objects. The table of Munsell x,y,Y -values, as defined under CIE standard illuminant C, published by Wyszecki and Stiles (1967) was completely stored on disk. We applied the SBC model to the set of 2734 Munsell specifications (see Figure 5a) and selected only those patches for which reflectances between zero and unity over the entire visible spectrum (380nm-770nm, steps of 10nm) were obtained (see Figure 5b). In Figure 6a-c the number of valid reflectance functions, as well as the total number of patches are given for Hue, Value and Chroma steps respectively. The distribution of samples with different Hue, Value or Chroma was not uniform in either the original or the restricted set. For example, the number of available samples decreases when Chroma increases (Figure 6c) or when Value differs more from 5 (Figure 6b). For the Hue category this relation is less simple. Whereas the original set contains minima in

the Yellow and Blue regions of the color triangle, the restricted set contains minima in the Red and Green regions. Both sets have maxima in the Purple regions.

From these data it is obvious that a relatively large number of patches (over 50%) had to be excluded from further analyses. Probably because Cohen performed an eigenvector analysis on a sub-selection of only 150 Munsell reflectance spectra (out of 433), his set was not a representative sample for the entire Munsell Book of Color. If basis functions are obtained for only reflectance spectra of Munsell papers giving color percepts that are not too extreme, i.e., small Chroma and Value close to 5, one would indeed expect problems if these particular basis functions are used to reconstruct reflectance spectra for more extreme colors. The two examples Cohen presents, patch R 6/6 and patch N 4/, do not offer counterevidence for this interpretation.

Although Cohen's basis vectors contain a consistent bias, we do not worry about the consequences. Our only goal is simply to obtain a set of reflectance spectra that provide specified tristimulus values under CIE standard illuminant C, and are between zero and unity in the range of 380nm to 770nm.

Additional tristimulus models

Because the spectral sensitivity functions of the human photoreceptors are used in the von Kries model, its outcomes are relatively easy to comprehend. However, from the point of view that we adopt in this paper, i.e., predicting tristimulus values of object color under changing illuminations, there is no fundamental reason to choose this particular tridescriptor representation of object color. In fact, the method underlying the von Kries model can be applied to whatever set of three primaries, simply by replacing L , M , S in equations 7 and 8 by alternative primaries. In this study we added CIE 1931 X , Y , Z , and phosphor luminances of a CRT color monitor R , G , B (see Lucassen and Walraven, 1991 for a related approach) to the models that can be used to predict tristimulus values.

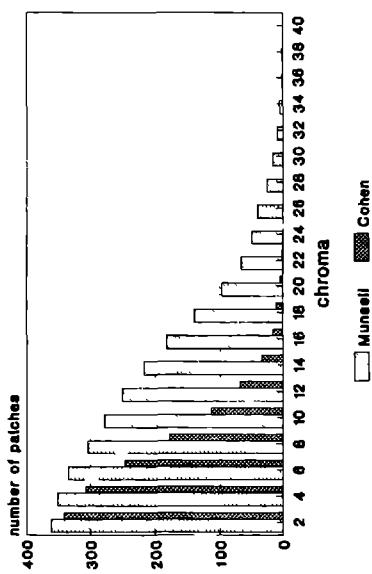
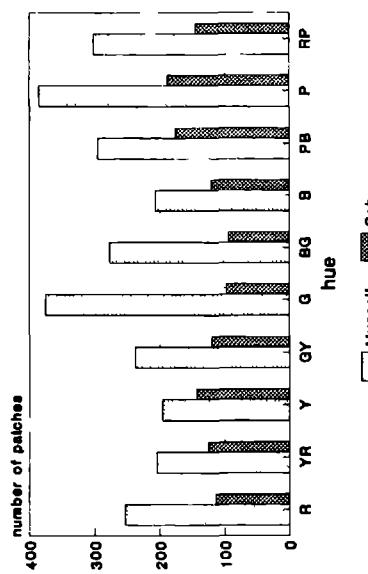
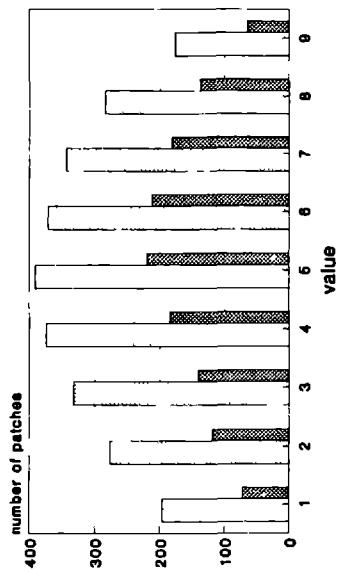


Figure 6. Total number of patches in the unrestricted (darker bars) and restricted stimulus set by (a) Hue, (b) Value and (c) Chroma. The latter only contained those patches for which a SBC-spectrum could be generated that was between zero and unity for all wavelengths.

Phosphor luminances R, G, B can be obtained from,

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} x_R/y_R & x_G/y_G & x_B/x_B \\ 1 & 1 & 1 \\ z_R/y_R & z_G/y_G & z_B/z_B \end{bmatrix}^{-1} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad (14)$$

Substituting chromaticities of the phosphors of our particular CRT monitor gives,

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 0.7584 & -0.3281 & -0.1205 \\ -0.7645 & 1.3462 & 0.0400 \\ 0.0061 & -0.0181 & 0.0805 \end{bmatrix} \begin{bmatrix} Z \\ Y \\ Z \end{bmatrix} \quad (15)$$

and reversely,

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 1.7657 & 0.4628 & 2.4127 \\ 1 & 1 & 1 \\ 0.0914 & 0.1901 & 12.4603 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (16)$$

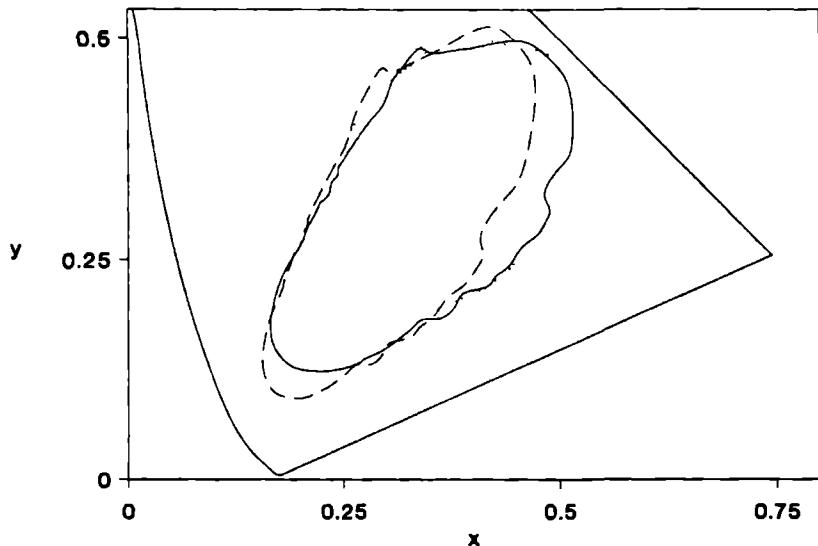


Figure 7. Predictions of the SBC model for 4000K (dotted lines) and 20000K (dashed lines) illuminants. Only the contours of x, y -coordinate clusters have been plotted. The solid contour specifies the restricted set under CIE standard illuminant C.

Procedure

As described above we chose a restricted set of Munsell patches, in which all corresponding reflectance spectra were bounded by zero and unity as generated by the SBC model. For every patch in the restricted set the illuminant invariant quantities, as defined under CIE standard illuminant C, were calculated, i.e., SBC, SBP, and van Trigt reflectance spectra, as well as L , M , S and X , Y , Z , and R , G , B ratios (see equations 7 and 8). Next, these illuminant invariant quantities were used in order to predict the resulting x , y -chromaticity values and luminous reflectance, Y , for each of the models and for each of the test illuminants. In Figure 7 the predictions of the SBC model under 4000K and 20000K illuminants are plotted.

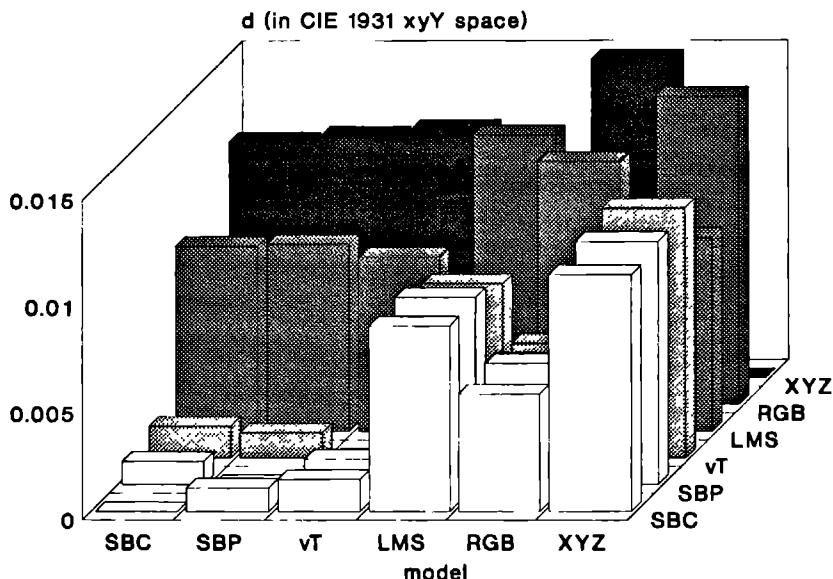


Figure 8. Average differences, taken over all illuminants and patches, between models in CIE 1931 x , y , Y color space. The height of the bar in each cell corresponds to the difference between the model from the bottom and the model from the right.

RESULTS AND INTERPRETATION

For illuminant p and Munsell patch q we calculated the Euclidean distance, δ , between the predictions of the i -th and j -th model (with $i < j$) in CIE 1931 x, y, Y color space,

$$\delta_{ijpq} = \{ (x_{ipq} - x_{jpq})^2 + (y_{ipq} - y_{jpq})^2 + (Y_{ipq} - Y_{jpq})^2 \}^{1/2}, \quad i < j \quad (17)$$

In Figure 8 the average differences for each pair of models

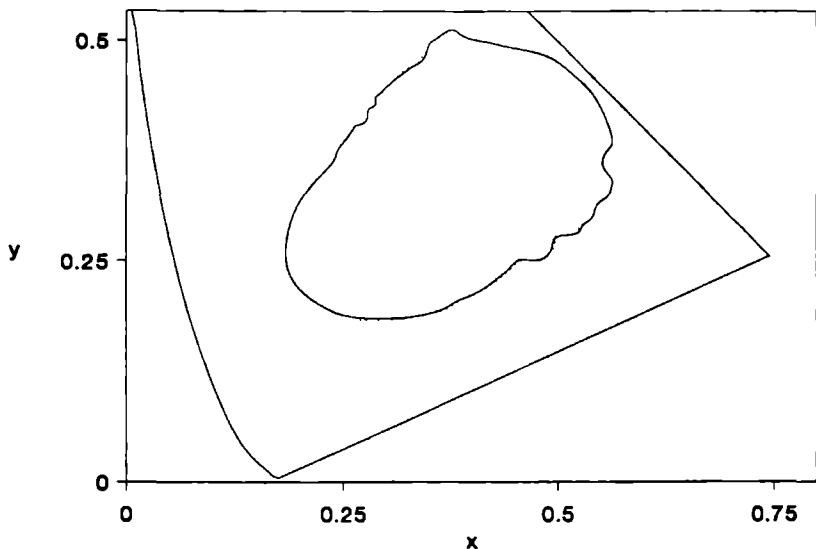
$$d_{ij} = \sum_{p=1}^9 \sum_{q=1}^{1323} \delta_{ijpq} / (9 \times 1323), \quad i < j \quad (18)$$

taken over all illuminants and Munsell patches, are displayed.

It can easily be seen that the average differences between the reflectance models, i.e., SBC, SBP and van Trigt, are very small (around $d = 0.0014$ x, y, Y -units). This means that the spectra generated by the SBC and SBP models are very close to the, mathematically smoothest, van Trigt spectra. Compared to the small difference of the reflectance models the differences among the three tristimulus models, L, M, S and R, G, B and, X, Y, Z are relatively large (around $d = 0.012$ x, y, Y -units). As can be seen, the choice of the primaries is critical, because if the SBC model is taken as a standard, R, G, B predictions are more accurate ($d = 0.0055$ x, y, Y units) than L, M, S ($d = 0.0087$) and X, Y, Z predictions ($d = 0.0111$). For theoretical reasons it could be wise to take the van Trigt model as the standard because in that model no particular assumptions about the existence of reflectances have to be made. Because of the fact that this model is not amply known yet, and because the SBC model is widely accepted, we took the SBC model as the standard. In Figure 9 the R, G, B and SBC predictions are compared for 4000K and 20000K illuminants.

Although there is no objective criterion to evaluate the impact of all these differences, there are three considerations that may be useful to interpret the magnitudes of differences. First, the difference between the models as a function of correlated color temperature of the illuminants, and Hue, Value and Chroma of the simulated Munsell patch, respectively. For instance, one may intuitively expect larger differences when more extreme illuminants and/or more saturated (high Chroma) Munsell patches are used. Second, the reproduction error of the algorithm to display a specified x, y, Y on a CRT monitor, and third the magnitude of perceptual differences, as expressed by MacAdam units, between predictions.

4000K



20000K

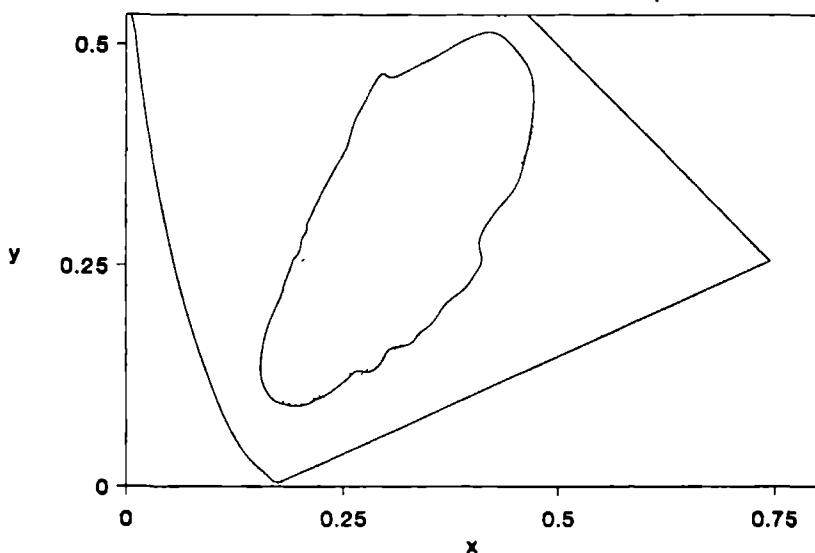


Figure 9. Contour plot of the comparison of SBC (solid lines) and R, G, B predictions (dotted lines) for 4000K (a) and 20000K (b) illuminants.

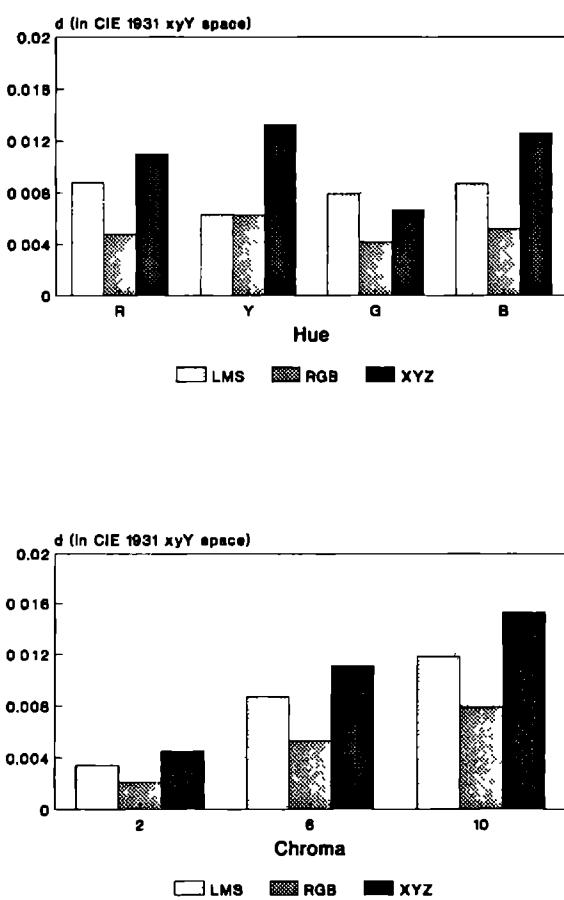
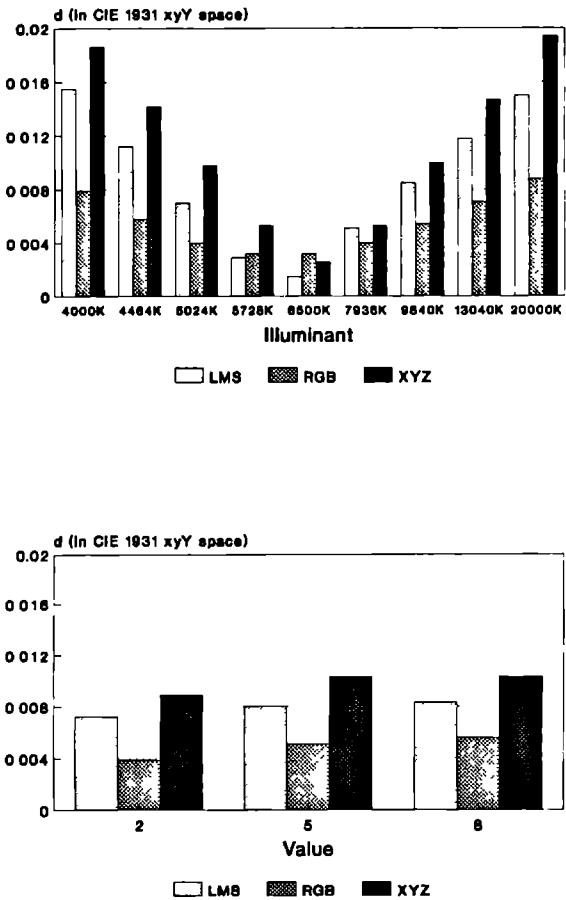


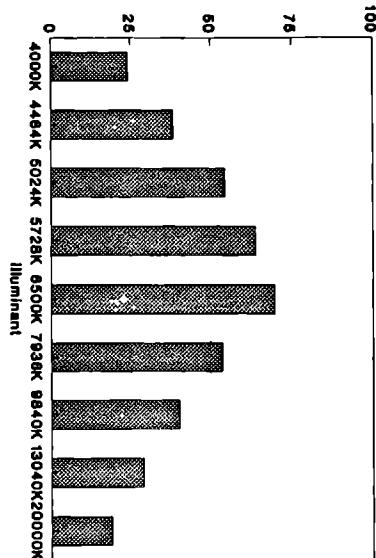
Figure 10. Average difference of the SBC model with other models by a number of (a) illuminants, (b) Hues, (c) Values and (d) Chromas.

Illuminant and Munsell specifications

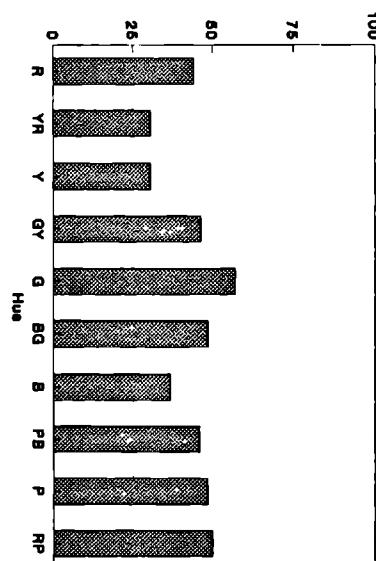
In Figure 10a-d the difference of the predictions made with the SBC model on the one hand, and the von Kries, phosphor and CIE 1931 tristimulus value predictions respectively, on the other hand, are displayed separately for (a) correlated color temperature, (b) Hue, (c) Value, and (d) Chroma.

As expected, d increases when test illuminants differ more from CIE standard illuminant C (6774K), and when more saturated Munsell patches are simulated. There is also a, less distinct, increase of d when Munsell Value increases. This holds for each of the three tristimulus models that were tested. The relation with Munsell Hue is less clear, but the R , G , B model gives the most consistent predictions ($d \approx 0.005$), as compared to the SBC.

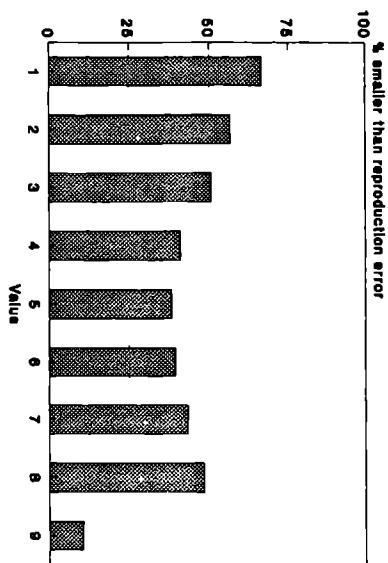
% smaller than reproduction error



% smaller than reproduction error



% smaller than reproduction error



% smaller than reproduction error

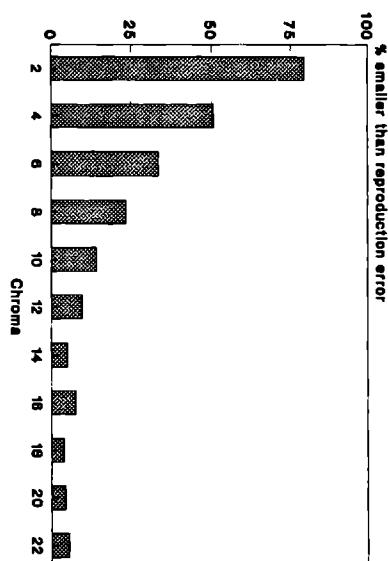


Figure 11. Proportion of patches leading to a difference between SBC and R , G , B that is smaller than the reproduction error of our particular monitor, by (a) illuminant, (b) Hue, (c) Value and (d) Chroma.

Reproduction error

Because simulations of surface color are mostly used for display on a CRT monitor, the degree to which a displayed color differs from the initial color specification must not be too large. Most commercial CRT monitors have luminance ranges, for each of the three phosphors, of only 8 bits wide and therefore it is impossible to cover all points in a continuous color space, simply because the luminance resolution is too low. For our particular monitor we obtained an average reproduction error of 0.0034 x,y, Y units with the restricted set of Munsell rennotations as input, and Value=5 ($Y = 0.1977$) set to 5cdm^2 . This means that the average difference between the SBC predictions and 1) van Trigt predictions and, 2) R, G, B predictions are in the order of magnitude of the average reproduction error.

Furthermore, we counted the number of pairs of predictions that differ less than the reproduction error for illuminants, and for some levels of Hue, Value and Chroma respectively. The resulting percentages are displayed in Figure 11a-d.

MacAdam units of color difference

To express the perceptual difference between the predictions of the SBC and R, G, B models, we calculated the MacAdam units of color difference for each simulated Munsell patch (see Wyszecki & Stiles, 1967). However, because MacAdam units are based on the comparison of pairs of stimuli of equal luminance, only x,y-chromaticity coordinates could be used and luminous reflectance, Y, had to be excluded from these analyses. This means that the luminances of the SBC and R, G, B predictions are necessarily assumed equal, and that only chromaticity is considered.

In order to obtain the major semiaxis, a , minor semiaxis, b , and angle, θ , of MacAdam ellipses for a large range of x,y-chromaticity coordinates, we interpolated the tabulated ellipse parameters given by Wyszecki and Stiles (1967) with a regression model of the form

$$P = \beta_0 + \beta_1 x^2 + \beta_2 x + \beta_3 xy + \beta_4 y + \beta_5 y^2, \text{ with } P \in \{a, b, \theta\}. \quad (19)$$

In Table I the regression coefficients, β , are given for each of the three ellipse parameters.

Table I

Regression coefficients, β_j , of the ellipse parameters, i.e., major semiaxis, a , minor semiaxis, b , and angle, θ , that define one MacAdam unit of color difference. In the lower row the proportion of variance, R^2 , that is accounted for by the regression model is given for each parameter.

	a	b	θ
β_0	-0.669453	0.148200	101.817975
β_1	-12.933332	5.625388	90.822039
β_2	6.849069	-2.363241	-284.739311
β_3	-26.307588	-6.348409	-72.989888
β_4	0.918061	6.965174	183.049163
β_5	20.919181	-3.384391	-186.942686
R^2	0.922	0.869	0.949

With these regression equations we calculated corresponding a , b , θ for each SBC prediction. Next, d_x and d_y are simply defined as the difference with R , G , B predictions

$$\begin{aligned} d_x &= x_{SBC} - x_{RGB}, \\ d_y &= y_{SBC} - y_{RGB}. \end{aligned} \quad (20)$$

Now, the number of MacAdam units of color difference, ds , is given by

$$ds = (g_{11}d_x^2 + 2g_{12}d_xd_y + g_{22}d_y^2)^{1/2}, \quad (21)$$

where parameters g satisfy the following relations with ellipse parameters a , b , θ ,

$$\begin{aligned} g_{11} &= a^2\cos^2(\theta) + b^2\sin^2(\theta), \\ g_{12} &= (a^2 - b^2)\sin(\theta)\cos(\theta), \\ g_{22} &= a^2\sin^2(\theta) + b^2\cos^2(\theta). \end{aligned} \quad (22)$$

The average number of MacAdam color difference units, ds , was found to be 2.474 over 9 (illuminants) \times 1323 (simulated patches) predictions. In Figure 12 the results are given for each separate illuminant.

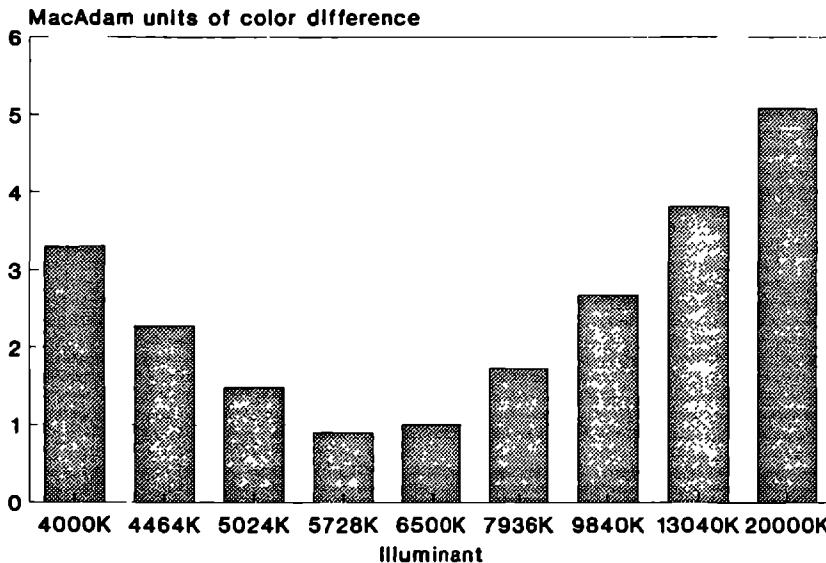


Figure 12. Average number of MacAdam units of color difference between the predictions of the SBC and *R, G, B* models by illuminants.

Because one MacAdam unit of color difference corresponds to approximately one third of a just noticeable chromaticity difference this means that a considerable proportion of pairs of predictions can not be discriminated by the visual system. Additionally, we counted the number of pairs of predictions with $ds \leq 3$ for illuminants, and some levels of Hue, Value and Chroma respectively. The resulting percentages are displayed in Figure 13a-d.

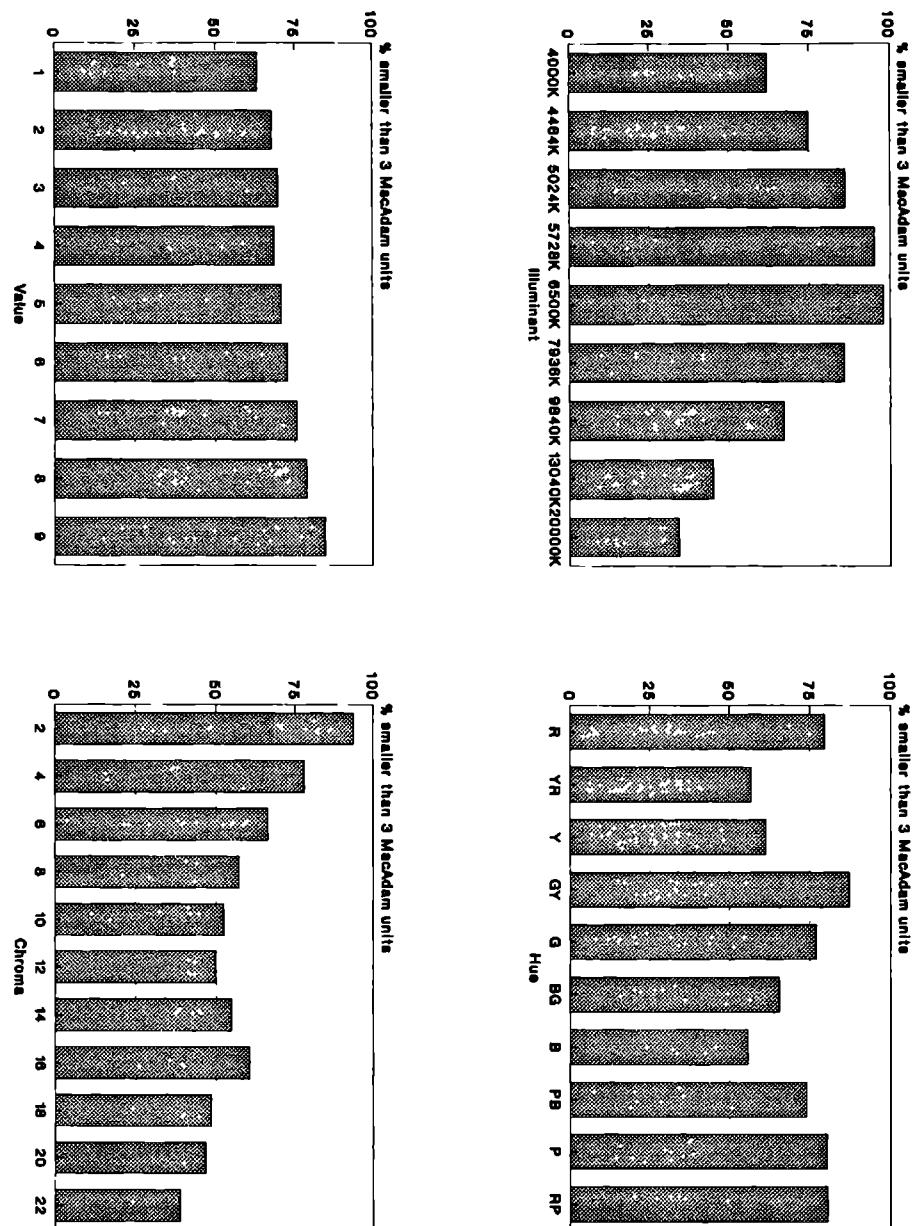


Figure 13. Proportion of patches leading to a difference between SBC and R , G , B that is smaller than three MacAdam units of color difference (= one jnd) by (a) illuminant, (b) Hue, (c) Value and (d) Chroma.

CONCLUSION

In this paper we described the performance of a number of models that can be used to predict object color under changing illuminant conditions. It was found that the predictions of reflectance models, i.e., SBC, SBP and van Trigt, are nearly equal. More surprising was that by applying von Kries's model for chromatic adaptation to R , G , B phosphor luminances, illuminant invariant quantities are obtained that lead to a wide range of accurate tristimulus predictions as compared to the Sällström-Buchsbaum/Cohen model. Specifically when test illuminants do not differ too much from the standard illuminant (in this study CIE standard illuminant C) and when simulated patches are not too saturated a considerable number of R , G , B predictions are within three MacAdam units of color difference of SBC predictions. Generalizing these results, based on simulations of Munsell patches under nine phases of daylight, varying from yellowish (4000K) to bluish (20000K), one may conclude that the R , G , B model provides an acceptable method to predict tristimulus values under changing illuminants. The advantage of the R , G , B model is that it can be used when spectra models cannot, that is, when illuminant spectra are unknown.

APPENDIX A

In order to apply the von Kries transformation, x,y -chromaticity and luminance, Y , of an object have to be converted to receptor responses. In order to obtain receptor responses, using Vos-Walraven primaries (see Vos, 1978) a number of intermediate conversions are required. First, Judd's (1951) modification of the x,y -coordinates is applied to obtain x' , y' -coordinates and luminance, Y' . This relation is given by,

$$\begin{aligned}x' &= (1.0271x - 0.00008y - 0.00009) / (0.03845x + 0.01496y + 1), \\y' &= (0.00376x + 1.0072y + 0.00764) / (0.03845x + 0.01496y + 1), \\Y' &= Y.\end{aligned}\quad (\text{A1})$$

It should be noted that Y' does not exactly correspond to Y , however, as long as stimuli are not in the extreme saturated blue region of the x,y chromaticity diagram, the differences are negligible.

For a stimulus with chromaticity coordinates x' , y' and luminance Y' , the tristimulus values are given by

$$\begin{aligned}X' &= (x'/y')Y', \\Y' &= Y', \\Z' &= ((1-x'-y')/y')Y'.\end{aligned}\quad (\text{A2})$$

L , M , S are given by

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.1551646 & 0.5430763 & -0.0370161 \\ -0.1551646 & 0.4569237 & 0.0296946 \\ 0.0 & 0.0 & 0.0073215 \end{bmatrix} \begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix}, \quad (\text{A3})$$

To obtain chromaticity coordinates x,y and luminance, Y , from receptor responses L , M , S , the reverse procedure is followed. First,

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} 2.94483 & -3.50013 & -29.08968 \\ 1.0 & 1.0 & 1.00137 \\ 0.0 & 0.0 & 136.63030 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix}. \quad (\text{A4})$$

Then from tristimulus values to chromaticity coordinates x' , y' and luminance, Y ,

$$\begin{aligned}x' &= X'/(X'+Y'+Z'), \\y' &= Y'/(X'+Y'+Z'), \\Y' &\equiv Y'.\end{aligned}\tag{A5}$$

And finally to x, y and Y

$$\begin{aligned}x &= (1.00709x'+0.00008y'+0.00009)/(-0.03867x'-0.01537y'+1.03450), \\y &= (-0.00347x'+1.02710y'-0.00785)/(-0.03867x'-0.01537y'+1.03450), \\Y &\equiv Y'.\end{aligned}\tag{A6}$$

CHAPTER 5

SURFACE REFLECTANCES AND HUMAN COLOR CONSTANCY:
COMMENT ON DANNEMILLER (1989)¹

Dannemiller (1989) described a two-stage approach to color constancy embodying a psychophysical adaptation principle, von Kries's proportionality rule (von Kries, 1905; see also Worthey & Brill, 1986), and a mathematical description of illuminants and reflectances known as the *Sällström-Buchsbaum model* (Brill & West, 1986; Buchsbaum, 1980; Sällström, 1973). The concept of a two-stage adaptation model is well known (e.g., Benzschawel & Guth, 1984; Jameson & Hurvich, 1972; Werner & Walraven, 1982; Worthey, 1985) and versions of the Sällström-Buchsbaum model were quite popular in robot vision (e.g., Brill & West; D'Zmura & Lennie, 1986; Maloney & Wandell, 1986; 1986; West & Brill, 1982). Nevertheless, by explicitly combining these different types of model Dannemiller (1989) succeeded in bringing studies on human and machine vision closer together. But despite Dannemiller's significant contribution, the starting point of his approach might well be fundamentally flawed as far as the human visual system is concerned. Before presenting our arguments, a brief description of basic assumptions of Dannemiller's approach relevant to our discussion is given.

The inclusion of the Sällström-Buchsbaum model means that Dannemiller's approach shares its rationale: Recovery of the reflectance properties of objects, the only relevant physical entity to remain constant under different illumination conditions, enables a visual system to achieve perfect color constancy. According to the Sällström-Buchsbaum model, reflectance properties can only be made available if two different types of constraints are met. The first type of constraint concerns the physical world and states that reflectance and illuminant spectra must be adequately described by a linear combination of three basis vectors. The second type concerns the visual system and deals with the representation of constants which are assumed to be known. These constants are obtained by combining receptor sensitivity spectra, two sets of basis vectors for illuminants and reflectances, respectively, plus a reference reflectance function.

¹ Troost, J. & De Weert, Ch. (1991). *Psychological Review*, 98, 143-145.

Dannemiller and others who work with computational models attempt to model perfect color constancy. In fact, human color constancy is only approximate (e.g., Arend & Reeves, 1986; Helson, 1938; Beck, 1972; McCann, McKee & Taylor, 1976; Werner & Walraven, 1982;). This implies that either the human visual system's estimates of surface reflectance are biased or that surface reflectance is not the description used by the human visual system to represent object color.

As Dannemiller (1989) points out, the Sällström-Buchsbaum model has difficulties with illuminants containing only a small number of wavelengths. Because such illuminants can not be described as a linear combination of three basis vectors, errors will be introduced in the computed spectral reflectance functions. It is interesting to see how the human visual system behaves under such conditions. In fact, McCann et al. (1976) studied human color constancy under conditions where three narrowband primaries were used for the illuminant. Although color constancy was not perfect, we disagree with Dannemiller's interpretation of McCann et al.'s data that were reconsidered by Worthey (1985). The data do not reflect a poor performance of the human visual system, as Dannemiller suggested. McCann et al.'s data demonstrate that the human visual system would be able to operate under conditions with strongly peaked illuminant spectra. In our view the study of McCann et al. cannot serve as an argument in defense of the imperfection of the Sällström-Buchsbaum model in operating under these conditions.

Given the second constraint, a principal objection against extending the Sällström-Buchsbaum model to the human visual system is that a mathematical solution to the problem of color constancy need not explain human color constancy. As we show, this misunderstanding is a result of the resemblance between the human visual system and the hypothetical visual system that Dannemiller (1989) proposed. In addition, we compare Dannemiller's color descriptors to an illuminant-invariant quantity that does not represent surface reflectance.

Although a vision machine can be constructed according to a mathematical description of illuminants and reflectances, there is no reason to assume that this description can be applied to the human visual system. The critical point in the Sällström-Buchsbaum model is the assumed availability of constants. The storage or implementation of these constants in the human visual system is a logical consequence of the Sällström-Buchsbaum model, but it is hard to see how this would be accomplished. Dannemiller (1989) partly recognized this problem when he considered the apparent need of recalibration of these constants as a result of developmental changes in both receptor sensitivities and ocular

transmissivity. But the Sällström-Buchsbaum model can only have explanatory power for human color constancy if the presence of the required constants in our visual system is shown to be plausible. In fact, Dannemiller tried to make this plausible when he pointed to the similarity between his second-stage reflectance channel and Buchsbaum and Gottschalk's (1983) second-stage opponent channel.

Both second-stage channels decorrelate the outputs of first-stage receptors. Dannemiller (1989) referred to the criterion of optimal signal transmission, which is imposed on Buchsbaum and Gottschalk's (1983) opponent channel and not on his reflectance channel, but he did not mention the difference in interpretation. Whereas Buchsbaum and Gottschalk's opponent channel can be identified with known physiological entities, ganglion cells, it is uncertain whether these cells incorporate the basis functions required to render adequate descriptions of surface reflectances (D'Zmura & Lennie, 1986). The reverse holds for Dannemiller: The basis functions he used describe surface reflectance but they cannot be identified physiologically. Dannemiller was aware of this problem when he tried to find an implementation for both models: His proposal was to locate the opponent channel described by Buchsbaum & Gottschalk in the periphery of the visual system and to locate the reflectance channel he himself described in a higher level of the visual cortex. Two remarks can be made here. First, it seems unlikely that the human visual system drops the criterion of optimal signal transmission and produces redundancies after the opponent stage. Second, the final reflectance channel to which Dannemiller referred is inspired by Land's (Land, 1977, 1986a) retinex theory, which is fundamentally different from the one proposed by Dannemiller. First, no constants are required; second, comparisons over a scene are made independently within each of the three contributing systems; and third, the illuminant-invariant quantity is not surface reflectance but lightness, which can be seen as a biological correlate of integrated reflectance that is not used to reconstruct surface reflectance spectra. In our view, Dannemiller failed in making the representation of constants in the human visual system plausible. Therefore, his ontogenetic considerations are suggestive only in the sense that the Sällström-Buchsbaum model is not rejected as a human color constancy model.

A tendency encouraged by the Sällström-Buchsbaum model is that the hypothetical trichromatic visual system leads to a wishful correspondence to the human visual system. Trichromacy in this artificial visual system is a coincidental property of the Sällström-Buchsbaum model since the use of three is not based on theoretical considerations, but rather on the finding that illuminant and reflectance spectra can be approximated quite well by a linear combination of three basis vectors (Cohen, 1964; Judd, MacAdam &

Wyszecki, 1964). Since both the illuminant and reflectance recovering phase in Dannemiller's approach contain three unknown parameters, three known quantities, i.e., receptor outputs, are required to obtain a solvable set of linear equations. Clearly, the discussion of the human perceptual validity of Dannemiller's approach would be more transparent if the number of required basis vectors was unequal to three. In that case there would be no similarity left between the human and the hypothetical visual systems.

In Dannemiller's approach the color of a surface is represented in terms of a reflectance spectrum. The actual derivation of this spectrum is a redundant operation since the scalar multipliers for the three basis reflectance vectors already contain the illuminant-invariant information. Actually, illuminant-invariant surface color is represented by three parameters and in this respect Dannemiller's approach does not differ from descriptions of illuminant-invariant surface color that do not represent reflectances. Lightness as used in the retinex Theory (Land, 1977, 1986a) is an example of such a description. As we have shown above, Dannemiller's three parameter description cannot be conceptualized in terms related to existing visual structures while lightness can be plausibly related to double opponent cells (Daw, 1984; Livingstone & Hubel, 1984) and cortical areas (Land, Hubel, Livingstone, Perry & Burns, 1983; Zeki, 1980). Clearly, in human visual perception an interpretation that is allowed by the latter type of description is preferable.

The point we have tried to make is that although surface reflectance as used in Dannemiller's approach can be an appropriate illuminant-invariant quantity for machine vision, its plausibility for human perception has yet to be shown. The interpretation of the required 27 constants in terms of human perceptual entities is a serious difficulty. Thus far, an underestimation of this problem has led to a fixation on surface reflectances, in turn giving rise to an ambiguous discussion when the human visual system is involved. In our view, reflectance might very well be a wrong choice as the surface color descriptor as used by the human visual system to achieve color constancy. Instead some illuminant-invariant quantity not restricted to representing reflectance might be better suited for human color constancy.

CHAPTER 6

In Chapter 3 it was shown that the apparent invariance of color perceptions cannot be solely due to known automatic peripheral processes (i.e., chromatic adaptation and lateral inhibition), which suggests that to achieve color constancy, other, more intelligent, processes are involved. The nature and characteristics of these additional processes have not been considered yet, and therefore this matter will be addressed in this final chapter. I will try to show that, for a better comprehension of the phenomenon of color constancy, it has to be released as a special color perception phenomenon, and has to be placed in the more general context of object perception. As such, it is strongly connected to the processing of figural properties in the visual image.

Katz (1911/1935) distinguished a number of qualities of color appearance, two of which, i.e. aperture color and surface color, are studied in color constancy research (e.g., Arend, Reeves, Schirillo & Golstein, 1991; Beck, 1972; Helmholtz, 1867/1962; Hering, 1874/1964; see also chapter 3). Whereas the former quality refers to color presented in isolation, surface color denotes the belongingness of color to an object. If chromatic color is considered as an expansion to three dimensions of achromatic color (Land, 1977, 1986a), brightness and lightness per color dimension are used as measures of the strength of sensation for aperture color and object color, respectively. Brightness is psychophysically assessed by light intensity, and lightness by surface reflectance. An observation described by Hering (1874/1962, p.10) clarifies the difference,

"...If I stand with my back to a window, hold a piece of smooth, dark-gray paper in front of me, and look with two eyes alternately at the paper and at the white-painted wall of the room behind it, then the latter appears white and the former dark gray [lightness], although the paper because of its much stronger illumination is of much stronger light intensity than the wall. Now, without changing the position of the paper or of my head in any way, let me fixate the upper edge of the paper with only one eye and try to see the colors of the paper and the wall in one plane: now indeed the wall appears darker than the paper [brightness]."

In this example, the surface color mode, in which the color sensation is determined by lightness, is dominant. In order to obtain the qualitatively different brightness sensation,

the observer had to force himself into the aperture mode, an impoverished viewing condition, in which depth information is prevented from being processed, and only the target fields are fixated (see also Gilchrist, Delman & Jacobsen, 1983). The dependency of color sensation on the reflectance distribution when a scene is observed in full complexity, is clearly demonstrated by this kind of observations. The notion of complexity is crucial here. At the beginning of this century, complexity implicitly referred to the variability in the intensity distribution, due to shadow, penumbra, gradients and three dimensional orientation, that could be taken as informational cues of the illuminant (for reviews see Beck, 1972; Henneman, 1935; and MacLeod, 1932). Due to concentration on the achromatic domain, in combination with the lack of a unified theoretical framework, this work still remains relatively unknown.

A more important reason for the current unfamiliarity with this work, is the fact that the recent success of the Retinex Theory (Land & McCann, 1971) to predict color sensations based on lightness (Land, 1977; McCann, McKee & Taylor, 1976), suggested that the surface color mode can already be obtained if only a large number of differently colored fields are presented, even without those details that contain information about the illuminant distribution in a scene. This type of stimulus configurations, also called Mondrian patterns, represent a collage of coplanar matte papers that is homogeneously illuminated by a single light source. Following this stimulus restriction, complexity is related to the number of differently colored fields in a stimulus configuration. This implies that the surface color mode can also be obtained with artificial stimuli, and consequently, that color constancy can be studied in isolation, that is, without those additional features that contribute to the object appearance of the stimulus, like 3D shape and orientation, gradients, shadows, and texture. Clearly, from the experimenter's point of view this reduction in the number of stimulus variables is fortunate because stimulus descriptions become simpler and conditions can easier be controlled.

Indeed, color constancy experiments have primarily been carried out with Mondrian patterns (e.g., Arend & Reeves, 1986; Land, 1977; McCann, McKee & Taylor, 1976; Valberg & Lange-Malecki, 1990; Zeki, 1980; see also chapter 3). For the psychophysicist who is used to work with target/surround stimuli that are of extreme figural simplicity, and who mainly seeks explanations that incorporate taking contrast ratios, every multi-colored stimulus pattern is a complex one, if only because more spatial interactions are involved (e.g., Brainard & Wandell, 1986; Grossberg & Todorović, 1988; Land, 1986b; Reid & Shapley, 1988). However, compared to the complexity with which the visual system is confronted under more natural circumstances, where multiple illuminants, illuminant

gradients, highlights, and shadows as well as geometric variables, specular reflectance properties, texture of surfaces, have to be dealt with (e.g., Horn, 1986; Marr, 1982; Rogers, 1985), Mondrian patterns represent a class of visual input that puts much less demands on both figural and computational processing.

However, the suggestion that the visual system can be brought in the surface color mode by confronting it with a Mondrian pattern, was shown to be incorrect in chapter 3 (see also Arend & Reeves, 1986). It appeared that the switch from surface color mode to aperture mode, as in Hering's observation described above, can in fact easily be made in the opposite direction when Mondrian-like patterns are presented to observers. If observers, being in aperture mode, are instructed to adopt the surface color mode, that is, to interpret the color differences between two stimulus patterns as the result of changed illuminant conditions, color matches are based on inferred surface characteristics, rather than on the light reaching the eye. However, whereas in Hering's observation both aperture and surface color appearances emerge as direct sensations, of course depending on the mode that is adopted, the color matches in a Mondrian environment are based on reasoning about the direct aperture color sensations, i.e. "matching what one should see". In other words, the surface color mode can only be adopted when a scene is sufficiently complex, in the sense that direct sensations are generated. If it is not, because important details are omitted, the observer's color sensation is automatically built up in the aperture mode.

Because the visual system has evolved under complex natural viewing conditions, the surface color mode can be taken as a default setting, giving the most reliable estimations of object color. If confronted with a much simpler scene, the visual system tries to make the best of it, and color sensations are based on spectral intensities. However, this does not mean that the latter information is eliminated or ignored in the surface color mode. On the contrary, the intensity distribution contains information concerning illuminants. Imagine a room with white walls that is illuminated by daylight through a window. The amount of light reflected from the walls decreases as a function of squared distance from the window, and produces different sensations of brightness, but only one lightness percept: Everywhere in the room the wall is assigned one and the same white. Although this kind of gradient can easily be solved by postulating some kind of threshold mechanism (e.g., Emerson, 1986; Grossberg & Todorović, 1988; Horn, 1974; Land, 1986a, 1986b), I prefer the type of explanation put forward by Cavanagh and Leclerc (1989) and Adelson and Pentland (1990) because it can be extended to cases that cannot be solved by merely making point by point comparisons of the intensity image, as

in existing algorithms (see discussion of Figure 1 below). These authors emphasize that because the origin of the light reaching the eye is an indeterminate problem, the visual system has to rely on some kind of implemented decision rules, or knowledge of physical reality, that restrict the number of possible solutions. For gradients the visual system apparently tries to fix the object component while allowing variation in the illuminant component.

Adelson and Pentland (1990) used minimal effort principles that can be taken as decision rules to solve the interaction between shape, illumination and reflectance. Although Adelson and Pentland's model is tentative and only adequate for a limited range of stimuli, their approach looks very promising for the investigation of surface color perception within a unified framework. Figure 1¹ is an example of how the figural organization affects the lightness percept.

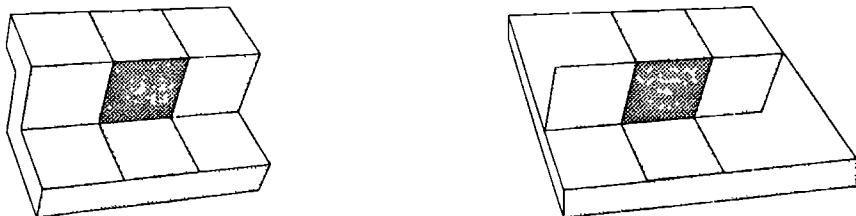


Figure 1. Two stimulus patterns in which the central areas (i.e., the dark quadrangle surrounded by four grey quadrangles) contain identical brightness distributions and shape relations. Figural analysis according to Structural Information Theory predicts a preference for the "step" interpretation (see text) for the right pattern (a), while the left pattern (b) is ambiguous towards the two alternative figural interpretations.

¹ This figure was kindly offered to me by Emmanuel Leeuwenberg

The central areas of both Figure 1a and 1b (i.e., the dark quadrangle surrounded by four grey quadrangles) contain identical brightness distributions and shape relations. A number of figural organizations of the central areas in Figure 1a and 1b are possible. I will discuss two alternatives: 1) the central areas are coplanar, and 2) they are arranged in a steplike shape. The crucial question is how the brightness of the central quadrangle is interpreted in either of the figural organizations. In the "step" interpretation the darkness of the central quadrangle is attributed to both decreased surface reflectance combined with the suggested shadow. In the coplanarity interpretation, a mosaic appears in which the darkness can only be attributed to decreased surface reflectance. If the figural properties of both Figure 1a and 1b are analyzed according to minimal effort principles as used in Structural Information Theory (see for example Leeuwenberg and van der Helm, in press) complexities are obtained for the coplanarity and "step" interpretations. The complexities of these different interpretations are dependent on the integration of the central areas in their corresponding contexts. If Figure 1a is subjected to such an analysis, a complexity of 10 units is obtained for the "step" interpretation, and of 17 units for the coplanarity interpretation. For Figure 1b 13 complexity units are obtained for both interpretations. These results suggest a strong preference for the "step" interpretation for Figure 1a, whereas Figure 1b is much more ambiguous because no preference is predicted.

Contrary to the algorithms mentioned above, the model of Adelson and Pentland predicts this difference. The central quadrangle in Figure 1a can be functionally discriminated from the one in Figure 1b, not because a more detailed mathematical description is used, but rather because the minimal effort principles, that are incorporated for both illuminant and object components on the one hand, and shape processing on the other hand, generate the most likely interpretation given the constraints the visual system is assumed to put on the input data.

To conclude, Adelson and Pentland's contribution is a formal description of the interdependence of processes underlying shape and color perception that was anticipated by Koffka (1935) from a Gestalt point of view. It is based on perceptually constraining the input data by mechanisms that incorporate implemented decision rules, or intuitive knowledge of physical reality. These mechanisms are probably centrally located, and as such they can be conceived of as instances of the central factors that Helmholtz and Hering thought to be important. Because color constancy is only partially determined by peripheral mechanisms that can be studied in isolation, i.e. chromatic adaptation and lateral inhibition, the remaining variations must be resolved by central

mechanisms that are also strongly involved in the processing of figural properties of the input data.

SUMMARY

In this dissertation several aspects, that can be divided in perceptual (chapters 2 and 3) and computational (chapters 4 and 5), of color constancy are considered. Color constancy refers to the phenomenon that object color perceptions are almost invariant despite changes in illumination. The historical interest in color constancy is reflected in a large amount of varied contributions in the scientific literature from the second half of the nineteenth century. A number of researchers even stated that color constancy is the most crucial phenomenon in color perception. In the first chapter the historical development of color constancy research is briefly presented.

In Chapter 2 asymmetric matching data that were obtained with a binocular presentation method are presented. The main motivation was the question whether chromatic adaptation, one of the important mechanisms that contribute to color constancy, has evolved towards a better performance in the range of colors that are present in the natural image. For the eye adapted to a bluish illuminant for example the presence of an object with a deep yellow color is very unlikely. So, it was expected that the color difference between adapting light and target has an influence on the extent of chromatic adaptation. It was found that the color shift in the observers' matches that can be attributed to chromatic adaptation indeed has a maximum. The location of the maximum, however, was unexpected, i.e., color differences between target and adapting light that lie around 0.05 $u'v'$ -chromaticity units. Additionally, several models for chromatic adaptation were fitted to the data. It was found that, except for the simple von Kries model (von Kries, 1905), Retinex Theory (Land, 1986a) and difference contrast, a number of models gave good predictions for the L-wave and M-wave fundamental systems, but that predictions for the S-wave system were less accurate.

Chapter 3 contains a replication of the color constancy study conducted by Arend and Reeves (Arend & Reeves, 1986) as well as an alternative method that can be used for the study of higher order aspects of color constancy like memory, familiarity and perceptual organization. Besides a simultaneous presentation of standard and test illuminants, an experiment in which the illuminants are presented successively was also carried out. The results were similar to Arend and Reeves'. However, in the object matching condition of the successive experiment, an overestimation was found, instead of an underestimation,

of the illuminant component. Because the results of matching experiments are difficult to interpret, mainly due to their sensitivity to instruction effects, another type of color constancy task was introduced. In this task, subjects simply named the color of a simulated patch. It was found that, by applying such a task, a reliable measure of the degree of identification of object color can be obtained.

Several computational schemes that can be used for the simulation of object colors under changing illuminant conditions on electronic displays, are compared in Chapter 4. These schemes differ in the assumptions that are made concerning illuminant invariant quantities, and the amount of a priori information that is required. Especially this latter feature is of importance for computer graphics applications and theoretical color constancy research because in many instances information about illuminant and object characteristics is minimal. A large set of tristimulus values of Munsell papers, as defined under CIE standard illuminant C, served as input data. Next, illuminant invariant quantities were obtained for each computational scheme that were used to predict x,y-chromaticity coordinates and relative luminosity, Y, under nine different phases of daylight varying from 4000K to 20000K. It was found that the differences between so called reflectance models on the one hand, and theoretically less accurate tristimulus ratio models on the other hand, are small and in most cases within three MacAdam units of color difference (1 jnd).

Dannemiller's computational approach to color constancy (Dannemiller, 1989) that is based on the Sällström-Buchsbaum model (Sällström, 1974; Buchsbaum, 1980) is discussed in relation to human color constancy in Chapter 5. A reflectance channel that requires a priori information is shown to be less plausible for the human visual system than Dannemiller argues. The resemblance of Dannemiller's hypothetical visual system to the human visual system is misleading since it implies that surface reflectance is the illuminant-invariant object color descriptor the human visual system uses to achieve color constancy. However, an alternative type of descriptor is available that is not used to recover reflectance spectra. It has the advantage of allowing an interpretation that is preferable from a human perceptual point of view.

In the final chapter some implications for future color constancy research are formulated. The most important recommendation is that color constancy has to be studied in the general context of object perception, rather than as a special color vision phenomenon. It is argued that because the pattern of light reaching the eyes under normal conditions is so varied and complex, it is impossible to obtain color constancy by automatic peripheral

processing. Central mechanisms that are also involved in the processing of figural properties are demonstrated to be of decisive importance for the achievement of color constancy.

SAMENVATTING

In dit proefschrift worden een aantal aspecten, onder te verdelen in perceptuele (hoofdstukken 2 en 3) en computationele (hoofdstukken 4 en 5), van kleurconstantie beschouwd. Kleurconstantie is het fenomeen dat de waargenomen kleur van een object nagenoeg dezelfde blijft onder belichtingsveranderingen. De historische interesse in kleurconstantie komt tot uiting in een groot aantal uiteenlopende bijdragen aan de wetenschappelijke literatuur sinds de tweede helft van de vorige eeuw. Een aantal onderzoekers zag kleurconstantie zelfs als het meest essentiële verschijnsel binnen de kleurwaarneming. In het eerste hoofdstuk wordt een kort overzicht gegeven van de belangrijkste historisch ontwikkelingen binnen het kleurconstantieonderzoek.

In Hoofdstuk 2 worden asymmetrische matchingsdata die zijn verkregen met een binoculaire presentatiemethode gepresenteerd. De belangrijkste vraag in dit hoofdstuk is of chromatische adaptatie, één van de mechanismen die betrokken is bij de totstandkoming van kleurconstantie, zich gedurende de evolutie zodanig ontwikkeld heeft dat het betere prestaties levert in natuurlijke kleuromgevingen. In een omgeving waarvan de gemiddelde kleur blauw is, is het zeer onwaarschijnlijk een sterk verzadigd geel voorwerp aan te treffen. De verwachting was daarom ook dat de mate van adaptatie afhankelijk is van het kleurverschil tussen een testkleur en de gemiddelde omgevingskleur. Deze verwachting kon deels bevestigd worden, de kleurverschuiving in de matches van de proefpersonen die toegeschreven kunnen worden aan chromatische adaptatie vertoonde inderdaad een maximum. De plaats van dit maximum (bij kleurverschillen tussen test- en omgevingskleuren van 0.05 $u'v'$ -eenheden) was echter onverwacht. Behalve het verzamelen van empirische data werd de voorspellende waarde van een aantal modellen voor chromatische adaptatie bepaald. Een aantal modellen, behalve het von Kries model (von Kries, 1905), de Retinex Theorie (Land, 1986a) en het verschilcontrast, doen goede voorspellingen voor de L en M fundamentele kleursystemen. De voorspellingen voor het S-systeem waren echter minder nauwkeurig.

Hoofdstuk 3 bevat een replicatie van de kleurconstantie-experimenten die oorspronkelijk zijn uitgevoerd door Arend en Reeves (1986). Tevens wordt in dit hoofdstuk een alternatieve methode gepresenteerd die gebruikt kan worden voor de bestudering van de beïnvloeding van kleurconstantie door factoren van een hogere orde, zoals geheugen,

bekendheid, en figurale organisatie. In het replicatiegedeelte wordt behalve een experiment met simultane presentatie van standaard- en testbelichting, ook een experimentele variant waarin de belichtingen successief worden aangeboden, beschreven. De verkregen resultaten waren vrijwel gelijk aan die gerapporteerd door Arend en Reeves. Echter, in de object matching-conditie van het successieve experiment werd een overschatting in plaats van een onderschatting van de illuminantcomponent gevonden. Omdat de resultaten van matchingsexperimenten moeilijk te interpreteren zijn, voornamelijk vanwege de gevoeligheid voor instructie-effecten, werd een ander type taak ontwikkeld om kleurconstantiedata te verzamelen. In deze taak benoemen proefpersonen eenvoudigweg de kleur van een object in simulatie. Deze taak levert een betrouwbare index van de mate van identificatie van objectkleur.

Een aantal computationele schema's die gebruikt kunnen worden voor simulatie van objectkleur onder veranderende belichtingsomstandigheden worden met elkaar vergeleken in Hoofdstuk 4. Deze schema's verschillen in het soort aannamen die gemaakt worden ten aanzien van illuminant invariante parameters en de benodigde hoeveelheid voorkennis. Vooral de laatste soort aannamen zijn belangrijk in computer graphics toepassingen en theoretisch kleurconstantieonderzoek omdat hier vaak weinig informatie omtrent belichtings- en objecteigenschappen beschikbaar is. De invoerdata bestond uit een grote verzameling van tristimuluswaarden van Munsell papers, zoals gedefinieerd onder CIE standaard illuminant C. Vervolgens werden illuminant invariante parameters berekend volgens de bestudeerde schema's om daarmee de x,y -chromaticiteitscoördinaten en reeltieve luminositeit Y te bepalen onder negen verschillende daglichtspectra, variërend tussen 4000K en 20000K. De verschillen tussen de zogenaamde reflectantiemodellen aan de ene kant, en de theoretisch gezien minder nauwkeurige tristimulus ratio modellen aan de andere kant, zijn klein en in veel gevallen kleiner dan drie MacAdam eenheden voor kleurverschil (1jnd).

In Hoofdstuk 5 wordt Dannemillers computationele benadering van kleurconstantie (Dannemiller, 1989), die gebaseerd is op het Sällström-Buchsbaum model (Sällström, 1974; Buchsbaum, 1980), besproken in relatie tot kleurconstantie bij de menselijke waarnemer. Aangetoond wordt dat een reflectantiekanaal dat over een grote hoeveelheid voorkennis moet beschikken minder plausibel is dan Dannemiller beweert. De sterke gelijkenis tussen Dannemillers hypothetische, en het menselijke visuele systeem is misleidend omdat dit impliceert dat oppervlaktereflectantie de illuminant invariante parameter is die gebruikt wordt door het menselijke visuele systeem om kleurconstantie te bewerkstelligen. Alternatieven die niet gebruikt worden om reflectantiespectra te

reconstrueren zijn echter beschikbaar. De voordelen van deze alternatieven zijn dat ze interpretaties toelaten die vanuit het oogpunt van de bestudering van de menselijke waarneming de voorkeur genieten.

Tenslotte wordt in het laatste hoofdstuk een aantal suggesties voor verder onderzoek beschreven. De belangrijkste aanbeveling is dat kleurconstantie in de meer algemene context van object waarneming onderzocht dient te worden, in plaats van als speciaal kleurwaarnemingsverschijnsel. Omdat de samenstelling van het licht dat de ogen bereikt zo complex en veranderlijk is, is het onmogelijk om kleurconstantie te vertonen op basis van de werking van enkele automatische en perifeer gelocaliseerde mechanismen. Aangetoond wordt dat centrale mechanismen die ook betrokken zijn bij de verwerking van figurale kenmerken van noodzakelijk belang zijn voor kleurconstantie.

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CURRICULUM VITAE

Ik werd op 31 oktober 1963 geboren te Breda waar ik ook mijn jeugd doorbracht en het Newman College bezocht. In 1982 behaalde ik mijn Atheneum-diploma en ging psychologie studeren aan de KU Nijmegen. Tijdens mijn studie raakte ik vooral geïnteresseerd in de visuele waarneming, wiskundige modelvorming en kunstmatige intelligentie.

Daarnaast nam ik een aantal student-assistentschappen aan waarin ik vooral als programmeur of practicumdocent werkte. Mijn stage liep ik binnen de kleurgroep van Charles de Weert. Na het in 1987 met genoegen van de Faculteit der Sociale Wetenschappen behalen van het doctoraal Psychologische Functieleer, accepteerde ik een baan als AIO aan het Nijmeegs Instituut voor Cognitieonderzoek en Informatietechnologie (NICI). Binnen dit instituut verrichtte ik samen met Charles de Weert vier jaar onderzoek naar kleurconstantie. Het proefschrift dat U nu in handen heeft is hiervan het tastbare resultaat.

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