Colour constancy “explained”

Jeroen Granzier

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Kleurkonstantie “verklaard”

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De wereld wordt vreemder, het patroon ingewikkelder
Van leven en dood. Geen intens moment
Afgezonderd, zonder voor of na,
Maar een leven dat brandt in elk ogenblik
T.S. Eliot, East Coker.

Dwaling van de filosofen.- De filosoof gelooft dat de waarde van zijn filosofie in het geheel ligt, in het bouwwerk: het nageslacht vindt die in de stenen, waarmee hij bouwde en waarmee sindsdien nog vaker en beter gebouwd wordt: dus in het feit dat het bouwwerk gesloopt kan worden en toch nog als materiaal waarde heeft.
Friedrich Nietzsche

We hebben angst om de wereld juist te aanschouwen en om juist aanschouwd te worden.
Istvan Szabo, regisseur.

De enige kennis die het waard is om te onderzoeken is kennis over de konstante en niet veranderende eigenschappen van al dat wat is in deze wereld. Het probleem is dat deze kennis moet worden opgedaan in een wereld waarin alles voortdurend verandert.
Plato in Phaedo

Wat maakt heroïsch? – Tegelijkertijd zijn grootste leed en zijn grootste hoop tegemoet gaan.
Waaraan geloof je? – Dat het gewicht van alle dingen opnieuw moet worden vastgesteld.
Wat zegt je geweten? - Je moet worden die je bent.
Waar liggen je grootste gevaren? – In medelijden.
Wat heb je in anderen lief? – Mijn verwachtingen.
Wie noem je slecht? – Hem die altijd wil beschamen.
Wat is voor jou het meest humane? –Zorgen dat niemand zich hoeft te schamen.
Wat is het zegel van de bereikte vrijheid? – Zich niet meer voor zichzelf te schamen.
Friedrich Nietzsche

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1
General introduction

1.1 Colour vision

When we open our eyes during day time, the world appears to us in full colour. Colour vision is the capacity of an organism to distinguish objects based on the wavelengths (or frequencies) of the light they reflect or emit. But what we mean when we talk about 'colour' can sometimes be quite confusing, as people can mean different things by using the same terminology. Therefore, we will start by explaining what we mean by the different terms used in this thesis.

An object's colour can be described as varying along three psychological dimensions: hue, brightness and saturation. The dimension of brightness is easiest to understand. At one extreme, the stimulus is just barely visible, at the other extreme it is dazzlingly bright and painful to regard. The second dimension is hue. When we talk about an object's colour, we normally mean the hue of that object: grass has a green hue, a banana has a yellow hue etcetera. Hue is not easy to define. In general, the exact hue of a particular surface cannot be specified. Differences among colour-normal individuals would permit at best typical or average desriptions. For example, the colour that appears pure green varies among observers. The third dimension is saturation. Saturation is an attribute of visual sensation, in which is meant how pure the hue is. When the hue is pure (not mixed with white light) we say that the hue is saturated (e.g., intense, deep red). And when the hue is mixed with white light or is 'washed out', we say that the hue is desaturated (e.g., pink).

1.2 The physics of colour

White light has no colour. White light is a mixture of all the wavelengths in the visible spectrum. This fact was first discovered around 1665-1666 (Newton, 1671) by Sir Isaac Newton (1642-1727), who passed a beam of sunlight through a glass prism to find that it separated into what he called "a spectrum of colours". Three things are needed to see colour: a light source, a detector (e.g., the eye) and a sample to view. A 'red' apple does not emit red light. Rather, it simply absorbs more of the short and middle wavelengths of light shining on it than of the long wavelengths of light. The result is that the dominant long wavelengths of reflected light causes that we perceive the apple as being red.

In humans, the nervous system derives colour by comparing the responses to light from three types of cone photoreceptors in the eye. This idea was first proposed by the English physician Thomas Young (1773-1829) in his 'trichromatic theory" (Young, 1802) and was later adapted by Hermann von Helmholtz (1821-1894). The cones are sensitive to different portions of the visible spectrum. For humans, the visible spectrum ranges approximately from 380 to 750 nanometers (nm). By assuming elementary colour sensations, connected to the activity of photoreceptors (cones) it is possible to account for the colour appearance of the spectrum. Helmholtz was the first to propose that colour vision is the additive mixture of the elementary colour 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 and short wave cones, would signal more redness than greenness and blueness, thereby establishing the impression of a red hue.

Karl Ewald Hering (1834-1918) proposed an alternative theory to the trichromatic theory, in which he stated that although the sensitivities of the cones peak at different wavelengths, there is a large amount of overlap with regard to the frequencies of the light to which the three types of cones respond. Thus, our visual system is designed to detect differences between the responses of the different cones. We now know that the trichromatic theory and opponent colours theory of Hering are both correct but that the two theories simply reflect processes at different levels of visual processing.

Thus, in short, colour perception is not simply based on the wavelength of light but depends on the relative cone stimulation in the eyes. Therefore, the wavelength of light will not be our main concern in this thesis. Instead, we will focus on relative cone stimulations, which can be plotted in a so called 'colour space' (see below).

1.3 1931 CIE colour space

In 1931 the CIE (Commission Internationale de l'Eclairage) developed the x, y, Y colour system by introducing a colour space in which every colour can be assigned a particular point. A colour space is a system for describing the relationships between colours numerically. The x and y coordinates in this colour space define the colour and the Y represents the luminance. This system is often represented as a two-dimensional graphic (the luminance is often not shown), which more or less corresponds to the shape of a sail. All possible colours in this colour space are made by combining the elementary colours of red, green and blue. A disadvantage of this colour space is that distances in the 1931 CIE colour space do not say much about colour perception. For example, when the distance in colour space between two given colours is as large as the distance between two other colours, it does not mean that the perceptual difference between these colours is equally large. Because of the fact that the 1931 CIE colour space is so widely used, we will use this colour space throughout this thesis.

2.0 Colour constancy

When walking through a street at night, we can clearly see whether the living rooms of people are illuminated by a television set or by a light bulb. When sitting in a living room, the colour of objects around us do not change very much as a result of this difference in illumination (tv-set or tungsten illumination). In other words, our green carpet remains green no matter whether a tv set or a light bulb is illuminating the room. Still we can vividly see that the colour of light reaching our eyes is different in both illuminating conditions. This is a real example of colour constancy.

Colour constancy is the ability to perceive object colours as fairly constant, despite considerable changes in the spectral composition of the illuminant (Land, 1977). A green leaf, for example, looks green when viewed at dawn, dusk or at noon. The main problem in colour vision research is how the visual system recovers the colour of an object, considering that the spectral distribution of the light emanating from that object is the product of illumination and reflectance. The visual system has to disentangle these two elements by considering the chromatic context in which the object is seen. By separating illumination and reflectance, the visual system can discount the illuminant colour (Helmholtz, 1867/1962). We are then left with the problem that, because the light coming to our eye is the product of the reflectance and illuminance, our eye or brain could not determine reflectance unless the illumination is known and the eye could not determine illumination unless the reflectance is known. In general, across the field of view, neither the reflectance nor the illuminance is known. Because more than one factor influences the light that reaches our eyes (the 'proximal stimulus'), it is possible for the same object to give rise to a very different proximal stimulus as the illumination changes. This effect of the illumination can be so extreme that the proximal stimulus (the light reaching the eye) resulting from a blue colour chip in tungsten light can be the same as that from a yellow colour chip in sunlight (Jameson, 1985). In other words, across a range of conditions, the visual system produces a colour representation that is better predicted by the surface reflectance than by the light reaching the eye.

Ironically, the very success by which the colour vision system represents the world to us prevents us from appreciating this accomplishment. Newcomers (like I was) to the study of colour constancy become drawn in only when the challenge to veridical perception are laid out concretely. The question of how the visual system accomplishes colour constancy has been studied for over 100 years. For revieuws of the early theoretical and empirical work, see Woodworth (1938) and Katz (1935). Helmholtz (1866) was probably the first who discussed the problem of how the visual system should get rid of the confounding effects of the illuminant. He attributed constancy to central factors that were learnt and applied through a process of uncouncious inference. Hering (1874/1964) argued for a much larger role for peripheral mechanisms but still retained central factors which involved memory. The problem remained unresolved despite the lengthy period of study. In the, by now, classical experiment with the "colour Mondrian", Edwin Land showed by using a collage of rectangular sheets of coloured paper, that the perceived colour of an object depends on more than just the spectral distribution of the light reflected from that object and he thereby showed that colour constancy works remarkably well. In these experiments, two identical Mondrians were placed side by side, each one illuminated with its own set of three projector illuminators equipped with band-pass filters (more or less mimicking the spectral sensitivities of the three cone types) and independent luminance controls so that the long- wave ("red"), middle-wave ("green") and short-wave ("blue") illumination could be mixed in a desired ratio. When the illuminators were so adjusted that the same triplet of radiant energies were reflected to the eye from, for instance, a white paper in the left Mondrian and a red paper in the right Mondrian, the two papers in the Mondrians kept their original colour, despite the different illuminations. So physically identical stimuli can nevertheless provide many different colour sensations. These results indicate that surface colours retain their colour identity under a great variety of lighting conditions. In addition to these experiments, Land proposed his Retinex (retina- and- cortex) theory of colour vision (Land, 1964, 1974; Land & McCann, 1971). This theory states that a colour percept is the end-product of the independent processing of three "black and white" images from the retina, each image analyzed by one cone type, independent of the absolute flux of radiant energy (luminance), but correlated with the cone-specific reflectance of a surface. The question of how features of the retinal image are used to estimate the chromaticity of the illuminant was from then on one of the central questions in colour research. Because of the fact that the problem of colour constancy is an ill-defined problem, the visual system has to put additional spectral constraints on both the illuminant and the surface reflectances in order to achieve a unique solution to obtain colour constancy.

2.1 Failures in colour constancy

Sometimes the assumptions that the visual system makes in order to achieve colour constancy are wrong. Indeed, we need not visit a laboratory to observe large failures of colour constancy. One of people's favorite occupation could not exist without a dramatic failure of colour constancy; When you attend a movie, you view a flat white surface on to which is projected a complicated dynamic pattern of light; the illuminant. Your estimates of the surfaces in front of you likely corresponds to the filmmaker's conception of the film. You see people, cars, explosions and so on, just as the script of the film predicted. None of these objects or their surfaces are present and yet you 'see' them, ocassionally forgetting about the only surface truly present, the uniform white screen. The failure of colour constancy in your perception of surface colour could not be larger.

Back to the laboratory, experimental studies have measured significant changes in colour appearance of surfaces under different illuminants (Arend & Reeves, 1986; Blackwell & Buchsbaum, 1988; Valberg & Lange Malecki, 1990). Questions about colour constancy must be framed in conjunction with a specification of the scene ensemble; colour constancy can be very good in scenes rich in accurate cues to the illumination

(Brainard, Brunt & Speigle, 1997; Brainard, 1998; Kraft & Brainard, 1999) and almost non-existent in scenes containing few cues to the illuminant (Helson, 1934; Tiplitz-Blackwell & Buchsbaum, 1988; Maloney, 2002). It is rational to assume that if the essential components for achieving colour constancy could be identified, one or more of them would provide the key for understanding failures in colour constancy; The patterns of errors offer a strong constraint to theories of colour constancy. This way of reasoning turned out to be disappointing, possibly because of the fact that each individual component adds only little to explaining colour constancy and that it is more likely that colour constancy is realized by a combination of these components. Thus, so far only a limited range of errors in colour constancy have been explained by such components.

2.2 Colour constancy and chromatic induction

Traditionally, theories have sought a unified explanation for illumination-independent successes (colour constancy) and background– dependent failures (chromatic induction). We will follow this tradition. When a white surface is surrounded by a red annulus, it appears greenish. The perceived colour is shifted in the direction complementary to that of the surround; chromatic induction (simultaneous spatial colour contrast). From demonstrations like these and from experiments which evaluate the influence of the surround on a surface's apparent colour percept, we can conclude that the colour of a surface depends on the surround (de Valois et al.,1986; Jameson & Hurvich, 1961).

Chromatic induction can be seen as a misdirected attempt to maintain colour constancy: the visual system erroneously attributes (part of) the change in wavelength ditribution of the light to a difference in illumination instead of a difference in reflectance of the surrounding background. Colour constancy and chromatic induction are therefore interpreted as manifestations of the same perceptual mechanism (Walraven et al., 1987; Valberg & Lange-Malecki, 1990).

2.3 The nature of the solution

Many possible solutions have been proposed, but no model can fully explain human colour constancy (Valberg & Lange-Malecki, 1990; Smithson, 2005). Much of the current work (see also this thesis) on colour constancy aims to discover what weights the visual system gives to different sources of information (also known as "cues") under different natural settings. Each single cue adds little in explaining colour constancy but the combined information from cues present in the visual image makes that colour constancy is such a robust phenomenon (chapter 2 of this thesis). In general, there are two possible ways in which the visual system could achieve colour constancy.

A first method is to get rid of the illuminant component first. Examples of this solution are cone adaptation, the Retinex theory of Land and by using illuminant invariant properties (e.g., colour contrast or 'relational colour constancy, e.g.; Foster & Nascimento, 1994) in a scene.

A second solution would be to estimate the illuminant in order to discount it. By combining information or cues present in a scene with regard to the colour of the illumination (e.g., specular highlights, interreflections, shadows etc.), the visual system can estimate the colour of the illumination and then discount its confounding influence. We will refer to this theory as the 'illuminant Estimation Hypothesis' (see chapter 4 of this thesis).

2.3.1 Local versus global influences on colour perception

The perceived colour of a surface is influenced by that of others in its vicinity (see chapter 7 of this thesis). The influence of surrounding colours is known to decrease rapidly as their distance from the area under investigation is increased (Jameson & Hurvich, 1961; Walraven, 1973; Brenner et al., 1989; Brenner & Cornelissen, 1991). From these findings we can conclude that colour vision has spatially very local characteristics (less than 2 degrees of visual angle when measured at the fovea). However, surrounding colours that exceed this 2 degree limit in visual angle also seem to have an influence on surface colour perception, as a result of making eye movements (Lennie & D'Zmura, 1988; Cornelissen & Brenner, 1995). Although relying on the local colour contrast makes judgments of surfaces' colours much less sensitive to the colour of the illumination (Foster & Nascimento, 1994; Foster et al., 1997; Land & McCann, 1971), it would make the judgments depend on the colour of surrounding surfaces (Brenner & Cornelissen, 1991). To avoid excessive influences of the direct surrounding the visual system could use local colour contrasts throughout the scene. But this is only expected to result in better estimates if there is no overall bias in chromaticity within the scene (see chapter 5 of this thesis). Moreover, most studies that examined this option found a negligible influence of the number of surfaces within a scene on colour judgments (Amano, Foster & Nascimento, 2005; Brenner, Cornelissen & Nuboer, 1989; Valberg & Lange-Malecki, 1990). Brenner et al. (2007) studied how we match two surfaces' colours; whether we are matching the light coming from those surfaces or whether we are primarily matching the colour contrast with the background. To find out, we asked subjects to make symmetrical and asymmetrical colour matches on different backgrounds on a CRT and we analyzed the variability in their settings. Matches made with more complex backgrounds or with different colours near the surfaces showed that subjects give little weight to local colour contrast at the borders between the surface and the background. In chapter 5 we studied whether the visual system uses global influences (the average reflected light coming from a scene) to determine a surface apparent colour. The results from that study showed that the visual system indeed uses the global or average colour of a scene to estimate the illuminant's chromaticity, but that the effects are very small.

2.3.2 Chromatic adaptation

Some of the earliest proposals for explaining colour constancy have been the fact that photoreceptor sensitivity (gain) changes can contribute to discount the illumination (e.g., Brainard & Wandell, 1992; Brainard, 1998; Chichilnisky & Wandell, 1995; Webster & Mollon, 1995; Uchikawa et al., 1989; Murray et al., 2006).

One of the earliest and still most used adaptation models that was proposed as suitable for obtaining colour constancy was the so called "coefficient rule" of von Kries (1905). It states that the sensitivities of the three cone systems are regulated by cone-specific coefficients (gain-factors), which are inversely proportional to the preceding stimulation. Adaptation causes the sensitivity of each of the three cones to change in such a way that the bias in the dominant wavelength of light caused by the spectral composition of the light is eliminated. Being one of the earliest models of colour constancy, the problems with this model is that even under circumstances when adaptation can play no role, colour constancy is still present (Land, & McCann, 1971), although its magnitude is reduced. It is mainly for these reasons that the role of von Kries adaptation has been debated (Worthey, 1985). Although the von Kries principle gives a satisfactory prediction of colour matches made under different illuminants (Brainard & Wandell, 1992; Lucassen & Walraven, 1993) it does not necessarily imply a physiological mechanism acting at the cone level. The scaling could also take place at a higher level, even in cortical areas (Rinner & Gegenfurtner, 2000).

2.3.3 Illuminant Estimation Hypothesis

Helmholtz proposed that the illuminant component in the light reaching the eye is judged at a central level in the visual system, based on past experience. The idea that remembered object colours may improve our estimate of the illuminant is a popular idea (e.g., Bramwell & Hurlbert, 1996). Support for the Illuminant Estimation Hypothesis comes from studies (e.g., Brainard, 1998) showing that observers' deviations from colour constancy can be parsimoniously explained by the assumption that subjects have misestimated the chromaticity of the illuminant.

However, in a study of lightness constancy, Rutherford & Brainard (2002) tested a version of the Illuminant Estimation Hypothesis in which the illuminant estimate is associated with the explicit perceived illuminant, and found it to be false. Chapter 4 of this thesis tests the Illuminant Estimation Hypothesis for the chromatic domain.

2.3.3.a Illuminant estimation as a combination of cues

The level of colour constancy achieved by human observers is typically less for simulated scenes than for real scenes (Schirillo et al., 1990; Agostini & Bruno, 1996; Brainard, Rutherford & Kraft, 1997; but see Savoy & O'Shea, 1993). The cause of the difference in magnitude between real and simulated scenes remains unclear because studies using different types of stimulus displays also differ in other aspects of the experiments.

An explanation for why illuminant discounting is much higher when using real scenes could be that the experimental stimulus contains many indications that it is correct to assume that the illuminant is chromatically biased, whereas simulated scenes do not contain such information unless it is specifically added, which it seldom is. An experiment of Yang & Maloney (2001) supports this type of reasoning. In this experiment, they used virtual scenes that were as real as possible, containing many cues to the illumination. Their observers achieved settings that compensated for 65% of the change in illumination. This result shows that their subjects discounted a higher amount of a difference in illumination when the scene was rendered in a manner that suggests that there was a change in illumination compared to the general results of studies in which no such change in the illumination is indicated (about 40% is discounted).

2.3.3.b The 'Grey World hypothesis'

In the 'Grey World hypothesis', the visual system arrives at the chromaticity of the illuminant by assuming that the illuminant is common to the entire visual field, and that the spatial average can provide an estimate of the illuminant, and the reflectance functions of the scene can be computed from this estimate (Buchsbaum, 1980). All the colours in the visual scene can then be scaled relative to this average. However, if the average reflectance in a scene is biased, like in a green forrest or the red bricks of a Dutch city landscape, normalization to the average gives an incorrect estimate of the illuminant. The advantage of basing the illuminant's colour estimate on the entire image is that excessive influences of the direct surrounding (surfaces adjacent to the surface of interest) can be avoided.

2.3.3.c The 'bright- is-white' hypothesis

The 'bright- is-white' hypothesis (Land & McCann, 1971) claims that the global colour of the brightest patch in the scene could be used as a cue to the illuminant's chromaticity, on the grounds that, as the surface apparently reflecting the most light, it is most likely to be white, and therefore most likely to provide an unbiased estimate of illuminant colour. Linell & Foster (2002) performed experiments in which observers were asked to make matches of the illumination across patterns (7 deg of visual angle) in which the global mean and the brightest patch were chosen to predict conflicting illuminants. With very small patches (0.03 deg of visual angle), illuminant estimates were set by the global mean (The Grey World hypothesis). The brightest patch had an effect only for the largest patches (1 deg of visual angle). Linell and Foster conclude that for flat richly sampled

Mondrian type stimuli the global mean is the dominant cue to the illuminant.

2.3.3.d Second-order statistics

Golz & MacLeod (2002) have suggested a more sophisticated version of the bright- is- white hypothesis by stating that luminance-colour correlations within an image may provide illuminant estimates that are less influenced by the set of reflectances available. In chapter 7 of this thesis we will return to this issue. In that chapter we explored whether luminance-colour correlations are used locally or globally by the visual system, as described in the section below. The results of chapter 7 show that luminance-colour correlations are too local in nature to give a reliable estimate of the illuminant's chromaticity.

2.4 Measuring human colour constancy

Two kinds of tasks mostly used in colour constancy experiments, to study the effects of context on colour appearance, are colour matching and achromatic judgments. In the former, observers have to match the colour of a test surface seen under one illuminant to the colour of a reference surface seen under a second illuminant (McCann et al., 1976; Arend & Reeves, 1986; Arend et al, 1991; Brainard & Wandell, 1992; Troost & de Weert, 1991; Lucassen & Walraven, 1993).

Achromatic settings have been used to understand chromatic adaptation and chromatic induction (Werner and Walraven, 1982; Bauml, 1994; Fairchild and Reniff, 1995; Brainard, 1998). When making achromatic judgments, subjects have to adjust a test patch' colour to appear a neutral colour. This patch can either be presented on a CRT in which case the colour of the patch itself can be changed or the patch can be a real surface in which case the colour of the patch can be made achromatic by adjusting the illumination that illuminates the surface. If an observer is colour constant, then the illuminated surface should continue to appear neutral under different lighting conditions (Fairchild & Lennie, 1992; Brainard, 1998). Higher levels of colour constancy have been obtained when using achromatic judgments (Kraft & Brainard, 1999; Delahunt & Brainard, 2004a; Brainard, 1998) than when using colour appearance matching (Bauml, 1999; Brainard, Brunt & Speigle, 1997; Delahunt & Brainard, 2004b). This shows that the degree of colour constancy depends on the kind of task used (Troost & de Weert, 1991, but see Speigle, 1997).

There are important differences between using achromatic settings and when using asymmetrical matching; there will be differences in viewing strategies between the two tasks, which influence the color settings that people make (Cornelissen & Brenner, 1991, 1995). In a matching task, subjects move their eyes from the test to the adjustable disk. When making achromatic settings, subjects fixate on the adjustable disk. Therefore, the state of adaptation will not be the same in both tasks.

The kind of instructions given to an observer can have a large influence on the amount of colour constancy obtained (Judd, 1940; Arend & Reeves, 1986; Jameson & Hurvich, 1989; Bauml, 1999). For example, Arend & Reeves (1986) reported a higher degree of colour constancy (60-70%) for a matching task on a CRT monitor when observers were instructed to make a match to make the two patches appear identical 'as if it looked as if they were cut from the same piece of paper' ('paper match') than when subjects had to make a match as if both patches were matched in 'hue, saturation and brightness' ('appearance match'). One important explanation for this discrepancy in results between the two instructions is that subjects are explicitly instructed to ignore (or to attribute) the object's appearance change as a result of the illumination when instructed to use a paper match. When using an appearance match, subjects have to infer from the visual cues in the scene to what extent a change in illumination contributes to the light that reaches their eyes. Therefore, the interpretation that subjects give with respect to attributing the dominant colour of the light coming from a scene as being the consequence of a bias in the illumination or of a reflectance change, has an effect on the degree in which the illuminant is discounted. This is a problem, as there is a large variability in the way in which subjects interpret whether a change in the light coming from a scene is caused by a change in illumination or by a change in reflections or in the degree in which subjects understand the kind of instructions given to them (Cornelissen & Brenner, 1995). In chapter 3 of this thesis, we tried to influence our subjects' interpretation by making it more plausible that there was a change in illumination causing a change in the light reaching their eyes. The advantage of the method or task that we used in chapter 3 is that there is no need to explicitly instruct subjects to discount the illumination. Often results of experiments using different methodologies, as explained above, are compared in colour constancy research, without explicit acknowledgement that these experiments and their underlying processes may be different.

3.0 Scope of this thesis

In the experiments presented in this thesis we used a colour monitor and real objects and real illuminants. Using a CRT or using a real scene has certain advantages and disadvantages; the computer monitor has the advantage of flexibility in the design of stimulus characteristics and allows a good deal of automatized data processing. However, a CRT requires repeated colorimetric calibration, can only be used with lower luminance levels, has a restricted colour gamut, and has a more limited viewing angle. Also, the self-luminous patches of colours on a CRT monitor are qualitatively more similar to light sources than to surfaces. We find it misleading to attribute an error to the visual system when the stimulus is locally impoverished or when it contains few illuminant cues, as is the case when using a CRT to simulate reality.

Using real scenes has the advantage of measuring constancy with a realistic setting in which all of the essential cues to the illuminant are available to the observer. However, data collection cannot be automatized and there is a limited extend to which the stimulus can be manipulated. As we found it essential to incorporate all essential cues to the illumination in our experimental scenes, we chose to use real scenes in most of our experiments.

4.0 Preview

Here I present a brief overview of the studies comprising this thesis.

Chapter 2 focuses on testing whether colour constancy is good outside the laboratory. Studies of colour constancy when tested inside the laboratory have found considerable deviations from perfect colour constancy. By using a method of forced choice we found that colour constancy performance was good enough for the task for which it evolved; to support identification of objects on the basis of their colour under changes in illumination.

In chapter 3, we tested whether subjects attributed more of the differences between light from different parts of the background to the illumination if the scene was rendered in a manner that suggested that there was a difference in illumination. We found a very modest level of chromatic induction, indicating that realistic rendering of a gradient in illumination does not increase chromatic induction.

Chapter 4 describes a direct test of the 'Illuminant Estimation Hypothesis' in the chromatic domain. We tested whether subjects' colour matches of lamps illuminating a real scene could predict their colour matches for wooden plates embedded in the same scene. The main prediction of the Illumination Estimation Hypothesis is that the visual system first makes an estimate of the illuminant and then determines the surface' reflectances by discounting the illuminant's colour. We found that subjects were poor in estimating the colour of the illumination. Their colour matches for the colour of the wooden test plates was much better. Therefore, we conclude that subjects did not use their estimates of the illuminant in order to achieve colour constancy but must have used illuminant invariant properties in the scene, like colour contrast.

In chapter 5, we tested the Grey World Hypothesis by asking subjects to match the colour and luminance of wooden plates that were embedded in scenes for which a Grey World assumption would lead to erroneous estimates of the plates' colour. We did not find the biases in colour perception that are predicted by the Grey World Hypothesis. Thus, we can conclude that our subjects did not give much weight to a Grey World assumption in order to obtain colour constancy.

Chapter 6 deals with trying to explain the differences in colour settings found between colour matching with a CRT and matching with real coloured papers (Pantone), as found in chapter 5. We wanted to investigate whether subjects make different colour settings when using a CRT, as they regard the computer monitor as a light emitting device (a light source) compared to when using real coloured papers (Pantone). We compared matches between colours that were both presented on a computer monitor or both as pieces of paper with matching the colour of a piece of paper with a colour presented on a computer monitor and vice versa. Our hypothesis was that if there is a fundamental difference between judging reflected and emitted light, the latter matches would be systematically poorer. Subjects' matches were indeed poorer but the main difference between the conditions was that subjects made larger errors when matching an image on a computer monitor to the colour of a piece of paper. We conclude that matching the light reaching the eye and matching surface reflectance are indeed fundamentally different, but that subjects cannot freely choose which to match.

Chapter 7 tests whether the visual system uses luminance-colour correlations in order to remove influences of the illuminant's chromaticity. We evaluated this by comparing different simulated scenes with matched luminance and chromaticity, but in which the correlation between luminance and chromaticity was manipulated locally. We found that there is indeed a bias in perceived colour away from the chromaticity of bright surfaces. However, both the results of colour matching and of making achromatic settings show that only the correlation within less than 1° of the target is relevant. Thus, this strategy is too local and therefore too unreliable to remove influences of the illuminant's chromaticity.

2
A real test of colour constancy

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A real test of colour constancy.

Abstract

In order to recognize objects on the basis of the way in which they reflect different wavelengths of light, the visual system must somehow deal with the different conditions under which the objects are seen. To test this ability under natural conditions, subjects were shown six papers simultaneously in a normally illuminated room, and instructed how to name them. The papers were easy to differentiate when seen together but they were so similar that subjects only identified 87% correctly when they were presented in isolation under otherwise identical conditions to those during the instruction. During the experiment, subjects walked between several indoor and outdoor locations that differed considerably in lighting and background colours. At each location subjects were asked to identify one paper. They correctly identified the paper on 55% of the trials, although the variation in the light reaching their eyes from the same paper at different positions was much larger than that from different papers at the same position. We discuss that under natural conditions colour constancy is probably as good as it can be considering the theoretical limitations.

Introduction

The light that is reflected from an illuminated object depends both on its surfaces' reflectance properties and on the illumination of the scene. If we are interested in the object's reflectance properties this raises a problem for our visual system, since the illumination can vary drastically over time and between locations, and can therefore have a considerable impact on the light that is reflected from the object onto the receptors in our eyes (Helmholtz, 1867/1962). This is the problem of colour constancy. The main advantages of having colour vision are to enhance the detection and identification of objects in the environment (Gegenfurtner & Rieger, 2000; Wichmann et al., 2002). For detection, a shift in illumination need not be a problem, but for identification a failure in colour constancy could be a hindrance. Probably many factors are involved in achieving colour constancy, including various kinds of spatial (e.g., Land, 1964; Granzier et al., 2005; Brenner et al., 2007; Brenner & Cornelissen, 1991; Brenner et al. 1989; Walraven, 1973; Tiplitz-Blackwell-Buchsbaum, 1988) and temporal (e.g., Von Kries, 1905; Lennie & D'Zmura, 1988; Cornelissen & Brenner, 1991) comparisons. Colour constancy in the laboratory is often poorer than in our everyday experience, and differs in extent between studies, probably because factors such as scene complexity (Kraft et al., 2002; Bloj et al., 1999; Gelb, 1950; Adelson, 1993; Gilchrist & Annan, 2002; Maloney & Schirillo, 2002), specular highlights (Yang & Maloney, 2001; Lee, 1986; Yang & Shevell, 2003; D'Zmura & Lennie, 1986), mutual illuminations (Bloj et al., 1999; Delahunt & Brainard, 2004b), shadows (Usui et al., 1996) and illuminant gradients (Brainard, Brunt & Speigle, 1997) can all contribute to colour constancy; and their presence differs between studies. Even with all the above mentioned factors available in a scene, colour constancy cannot be perfect because human colour vision is based on the comparison of signals of three types of cones in the retina. This constrains the identification of coloured surfaces under different illuminations (Nascimento, de Almeida, Fiadeiro & Foster, 2004; Foster, Amano, Nascimento & Foster, 2006; Young, 1987) as can be observed when matching clothes. After careful scrutiny in a store a match is accepted under fluorescent lighting, only to experience great disappointment when leaving the store and discovering that the match is no longer acceptable in daylight. In this case, what was a perfect match under one illuminant (fluorescent) is not a perfect colour match under another illuminant (daylight), because the reflectance in the store (the actual spectrum of the reflected light) was not the same, only the three receptor stimulations were the same. We here test colour constancy under natural conditions using stimuli for which colour constancy is likely to be the limiting factor for performance. We use quite similar colours of real objects (here coloured sheets of paper), but ones that are easy to categorize so that memory is not an issue.

Methods

Subjects

21 subjects (including two of the authors) with normal colour vision (Ishihara, 1969) took part in the experiment. This research was approved by the local ethics committee (Faculty of Human Movement Sciences, Vrije Universiteit, Amsterdam).

Procedure

For practical reasons, the experiment was performed in three groups of seven subjects. During an 'instruction phase', subjects were told how to name the colours of six different test papers that were presented simultaneously on a desk under daylight illumination (see figure 1). The test papers were white or very slightly grey, green, red, blue or yellow. After the task was explained to a group of subjects, they walked a tour passing 24 different pre-selected locations. Each group of subjects had to identify one test paper at each of the 24 locations. The papers

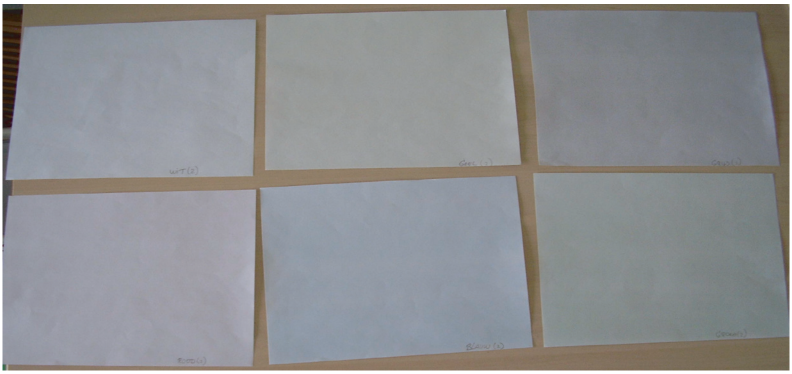

Figure 1.
The papers as first shown to the subjects during the instruction phase. Although this image is obviously not calibrated, it gives an impression of the difficulty of the task.

were presented in random order but ensuring that each test paper was presented four times. Subjects were not told that each paper would be presented 4 times. They wrote the name of the colour of the paper that they thought was being shown to them on an answer form. At each location, the experimenter presented the test paper separately to each subject. Subjects were allowed to hold the test paper in their hands and change its orientation. They could compare the test paper's colour to the colours of objects in the direct vicinity, but were not allowed to compare the colour of the test paper with their white answer form, and they

Figure 2. Examples of indoor and outdoor locations. The subject decides which paper he or the experimenter is holding.

had to remain at the place at which the experimenter had given them the test paper. Subjects were not allowed to talk about the experiment during the tour and were instructed to keep their answer form hidden from the other participants.

The locations

We used both indoor and outdoor locations (see examples in figure 2). Two walking tours were carried out inside and near the university campus of the Vrije Universiteit in Amsterdam. One walking tour was carried out both inside and outside the first author's house located in the south of The Netherlands. The walking tours were performed on days in which the weather conditions were likely to make outdoor colour constancy most difficult (blue sky with occasional clouds). About half of the locations were indoors while the other half were outdoors. There were locations in which only artificial illumination was present and ones in which the test papers were illuminated only by natural daylight, as well as ones in which both kinds of illumination were present (the instruction room was one of these). There were outdoor locations that were in the shadow of plants or buildings, and ones in direct sunlight. The final location was the one that we had used for the instruction phase. We included this location to see whether subjects would be particularly good in the environment in which they had initially seen all the colours. The experiment took about 90 minutes for each group.

Baseline

Although the difference between the papers was very clear when they were presented simultaneously, identifying them in isolation was quite difficult. In a separate measurement, we tested our subjects' ability to identify the test papers at a fixed place under constant fluorescent illumination (Philips, 38 HF; 50 watt). Five subjects who also participated in the main experiment took part in this baseline measurement. The CIE_{xy} coordinates of the light reflected by the test papers under these conditions, as measured with a Minolta CS-100A chroma meter, were (0.436, 0.404), (0.432, 0.406), (0.439, 0.402), (0.426, 0.401), (0.441, 0.411) and (0.436, 0.405), for the grey, green, red, blue, yellow and white test paper respectively.

The procedure was similar to that of the main experiment, but the background was always the same (the grey surface of a table) and the illumination did not change between the first simultaneous presentation and the subsequent test presentations. Thus, colour constancy was not an issue. After presenting all six pieces of paper simultaneously, the experimenter placed one of the six test papers on the table every three minutes, and the subjects had to write down which paper they thought was being presented (i.e. its colour). As in the main experiment, each test paper was presented four times, and the papers were presented in random order (24 trials). The three minutes waiting time was chosen to match the time between judgments in the main experiment. Subjects remained in the room during the 3 minutes between presentations.

Analysis

To illustrate the judgments that subjects made, pie charts were made per location and test paper. The corresponding colour of the reflected light was also indicated. Since subjects could move the papers around and the illumination could change slightly while the members of the group sequentially made their judgments, we measured the colour of the reflected light several times at each location for each group (while the subjects were making their decisions) and calculated the average CIE_{xyY} values. These averages are shown together with the above-mentioned pie charts.

That performance would not be perfect was expected because we chose shades of colours that were difficult to distinguish. The question is to what extent performance is worse than it was when papers were shown together when the illumination is different. To find out, we plotted the percentage of correct responses as a function of the distance in CIE colour space between the test papers' CIE_{xy} coordinates during the main experiment and during the corresponding instruction phase. We averaged consecutive groups of 6 presentations (a presentation is a set of 7 responses for a given combination of paper and illumination) after sorting the presentations in terms of the above- mentioned distance.

Results

The average number of correct responses during the main experiment was 55.4% (ranging between 37.5% and 79.2% for individual subjects; 16.6% is chance level). During the baseline, in which there was no change in illumination or in background colour and the subjects were fully adapted to the illumination, 87.5% of the responses were correct. That subjects made errors under these conditions demonstrates how difficult it was to distinguish between our papers' colours. The 5 subjects who participated in the baseline did not perform any differently than the other subjects in the main experiment.

In figure 3 each panel presents data for one of the six test papers. The disks indicate the average measured CIE_{xy} coordinates of the light reflected by the test papers at the different locations. They illustrate the colour shifts that the subjects had to deal with. For comparison, the crosses indicate the CIE_{xy} coordinates of the light reflected from the test papers during the baseline, when all papers were viewed under the same fluorescent illumination (coordinates given in the method section). This illustrates how small the impact of the differences in reflectance is in comparison with the impact of the illumination.
These coordinates are shown for illustration purposes; they do

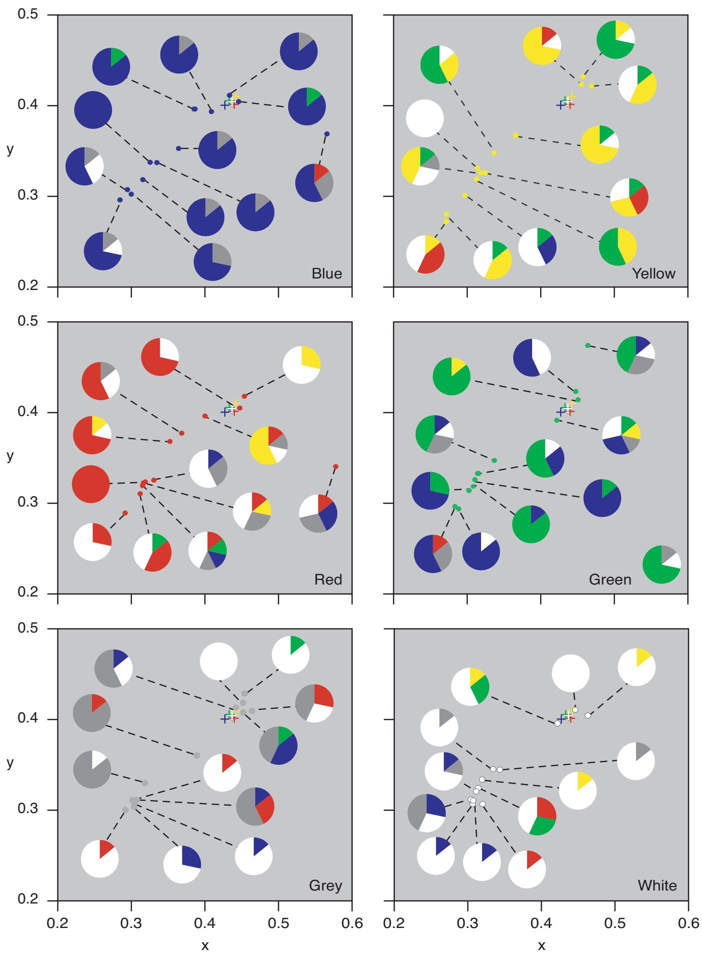

Figure 3.
Overview of the results. Each graph represents the results for one of the six test papers. The six crosses show the CIE_{xy} coordinates of the six test papers in the baseline condition (same in all panels). The disks show the average coordinates of the test papers when measured at the 12 different locations. Pie charts show the distribution of subjects' responses. The location corresponding with the pie chart for one green test paper (middle right graph) is absent because of technical problems when measuring the light during the presentation.

not coincide with the values shown during the initial part of the main experiment, which differed for the three groups of subjects. The measured luminance of the light reflected by the papers varied between 5 and 17100 cd/m^2.

The pie charts in figure 3 show the proportions of responses for each test paper at one of the twelve locations at which that paper was presented (to 7 subjects). The colours in the pie charts correspond with the names that the subjects wrote down. Figure 4 shows how the percentage of correct responses depends on how different the colour of the illumination is from the value during the instruction phase. Figures 3 and 4 highlight three aspects of the task.

First, the influence of the differences between the test papers' reflectance properties on the light that reached our

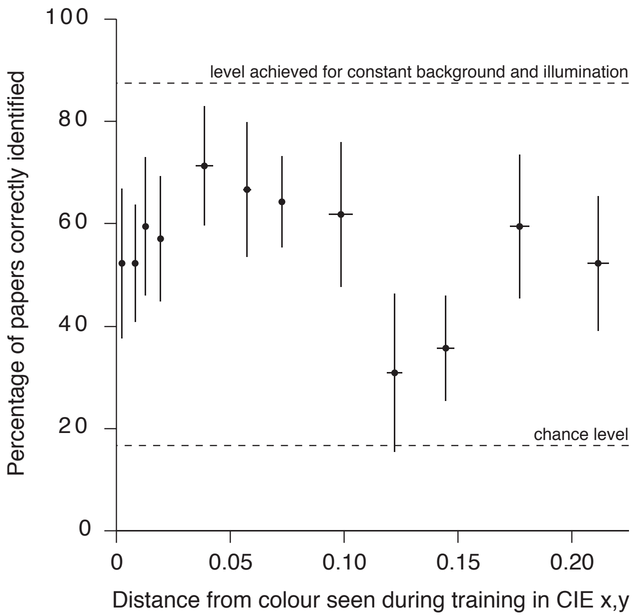

Figure 4. Performance as a function of the shift in chromaticity with respect to that in the instruction phase. Points are averages for 6 presented papers, with standard errors across the percentages correct for the 6 presented papers and across distances.

subjects' eyes (distances between crosses in figure 3) is much smaller than the influence of seeing the test papers at different locations (distances between disks in figure 3). This illustrates the problem that the visual system is confronted with when having to recognize objects (i.e to name the colour of the paper) in different settings at different moments.

Secondly, despite the large differences between the light reflected from the same test paper at the different locations, subjects were often able to recognize the test papers' colours (pie charts in figure 3). In fact, a large difference between the light reflected during the instruction phase and when tested in the main experiment hardly reduces subjects' performance (figure 4).

Finally, looking at the pie charts of figure 3, we see that subjects are only slightly biased, if at all, by the colour of the light that reaches their eyes from the surface of the paper. For example, when the dominant light that reaches the subjects' eyes is yellowish (top right of panels), we may have expected subjects to often erroneously identify the test paper as being the yellow paper.

Table 1: Summary of responses for each paper.

	Paper						
	White	Yellow	Red	Blue	Green	Grey	Total
Response							
White	57	28	32	3	7	5	132
Yellow	3	28	8	0	2	0	41
Red	9	6	29	1	1	7	53
Blue	5	2	4	67	32	8	118
Green	4	19	2	2	31	2	60
Grey	6	1	9	11	11	62	100

Table 1 shows the frequency of responses for each of the six test papers. Diagonal cells represent correctly identified test papers. Certain colours were chosen more often than others, and certain pairs of test papers were more frequently confused with each other than others. For example, the green test paper was often identified as being the blue and the yellow and red test papers were often identified as being white.

On average, subjects correctly identified 76% of the test papers when they were shown again at the location at which they had originally been presented. This was significantly better than average (chi-square=3.85, $p < .05$). It was slightly (though not significantly; chi-square=1.88) less accurate than in the baseline, perhaps because the illumination was no longer exactly the same and subjects had been exposed to very different illuminations between the instruction phase and this test.

Discussion

Although the papers were very similar to each other in reflectance, and both the colour and luminance of the illumination and the colour of the background varied considerably between the locations, subjects were able to identify the coloured test papers on more than half of the trials. Their performance did not appear to depend on how different the illumination was from the one under which they were instructed about how to name the papers (figure 4). There was a weak tendency at most to be biased by the colour of the light that reached the subjects' eyes from the surface of the paper. The improved performance when returning to the initial position is probably due to the background being the same as during training. Thus, colour constancy is extremely good for real objects presented under natural conditions when the task is to recognize surfaces by their colour.

There are two main reasons why colour constancy in general cannot be perfect. First, there are the theoretical limitations of trichromatic colour vision, as described in the introduction section, that constrain the identification of coloured objects under different illuminations. Secondly, since any pattern of light reaching the eye could arise from an infinite number of combinations of reflectance and illumination, the visual system has to make assumptions for separating the contributions of illumination from those of reflectance (e.g., Granzier et al., 2005; Granzier, Smeets & Brenner, 2006). These assumptions can be violated. Relying on multiple sources of information (as described in the introduction) can make colour constancy very robust, but considering the possibility that assumptions are violated constrains the amount of colour constancy that can be achieved even when the assumptions are not violated, and leads to errors when any of the assumptions are violated. Indeed, we need not visit a laboratory to observe large failures of colour constancy: when you attend a movie you view a flat white surface on to which is projected a complicated dynamic pattern of light. You see people, cars, explosions and so on, just as the script of the film predicted. None of these objects or their surfaces are present and yet you 'see' them, most of the time forgetting about the only surface truly present, the uniform white screen.

3
Does realistic rendering of a gradient in illumination increase chromatic induction?

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Does Realistic Rendering Of A Gradient In Illumination Increase Chromatic Induction?
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Abstract

Placing a background consisting of two parts with a different surface reflectance behind two physically identical surfaces makes the two surfaces look different from each other. This is a phenomenon known as chromatic induction. Chromatic induction can be seen as a misdirected attempt to maintain color constancy: the visual system erroneously attributes (part of) the difference in the light reaching the eye from the two parts of the background to a difference in illumination instead of a difference in reflectance. In the present paper we examine whether subjects attribute more of the differences between light from different parts of the background to the illumination if the scene is rendered in a manner that suggests that there is a difference in illumination. We simulated a single surface illuminated by an ambient illumination and a lamp with a different spectral power distribution near one of the two surfaces that subjects had to match. We found a very modest level of chromatic induction. Thus realistic rendering of a gradient in illumination does not increase chromatic induction.

Introduction

The color of the light that reaches our eyes depends on the spectral properties of the reflectance of the surfaces that we look at, as well as on the spectral power distribution of the illumination. Nevertheless, surfaces hardly change in color appearance when the spectral power distribution of the illumination changes: a phenomenon known as color constancy (Land, 1977). How does the visual system succeed in discounting the contribution of the illumination? There being a dominant color in the light coming from a scene can be the consequence of a bias in the illumination or of a bias in the reflectance of the surfaces in the scene. If the visual system assumes correctly that a bias in the dominant color of the light coming from the scene is the consequence of a bias in the spectral power distribution of the illumination, and consequently compensates for this bias, color constancy is achieved (Helmholtz, 1962). On the other hand, if the visual system erroneously assumes that a bias in the dominant color of the light coming from the scene is the consequence of a bias in the spectral power distribution of the illumination, and compensates for this bias, we experience chromatic induction. In accordance with this interpretation (Walraven, Benzschawel & Rogowitz, 1987), chromatic induction appears to be weaker in simple displays, in which it is evident that the surrounding surfaces have different reflectances, than in more complex displays, in which pictorial depth cues suggest that the illumination rather than the reflectance of the background is different (Lotto & Purves, 2002).

It is reasonable to assume that if the experimental stimulus contains many indications that it is correct to assume that the illuminant is chromatically biased, as is the case with real scenes, subjects will exhibit strong color constancy. In real scenes, about 80% of the illumination-induced bias in the color of the light reaching the eye is attributed to the illumination and ignored (Kraft, Maloney & Brainard, 2002; Brainard, Brunt & Speigle, 1997; Brainard, 1998; De Almeida, Fladeiro & Nascimento, 2004). Could the reason why only about 40% is attributed to the illumination in simulated scenes (Troost & de Weert. 1991; Cornelissen & Brenner, 1995; Yang & Shevell, 2003; Arend, Reeves, Schirillo & Goldstein, 1991; Lucassen & Walraven, 1996) be that in real scenes efforts are seldom made to remove direct information about the illumination, whereas simulated scenes do not contain such information unless it is specifically added, which it seldom is?

The classical way to measure chromatic induction is with a simple stimulus consisting of two disks each surrounded by an annulus (Shevell & Wei, 1998; Brenner & Cornelissen, 2002; Brenner, Ruiz, Herraiz, Cornelissen & Smeets, 2003). The stimulus itself is totally devoid of any indication that the differences between the dominant color in the light coming from the two annuli is a consequence of differences in illumination rather than of differences in reflectance. We wanted to investigate whether we could increase chromatic induction in rendered scenes by introducing a gradient of illumination and specular highlights to give the impression that the difference in the light from the background is caused by a difference in illumination. We asked subjects to match the appearance of two disks. We used various backgrounds, illuminants and intensities of the gradient to see whether any of these factors had an effect on the magnitude of chromatic (and luminance) induction.

Method

Apparatus

The stimuli were presented on a calibrated Sony GDM –F520 monitor (39.2 by 29.3 cm; 1024 by 768 pixels; 120 Hz; 8 bits per gun) in an otherwise dark room. Subjects sat 100 cm from the screen with their chins and foreheads supported.

The background

The 16 by 16 degree square background consisted of an array of 30 by 30 squares. In the 'fixed pattern' condition, there were only four different simulated surface reflectance's in the background, and they were arranged systematically (see Figure 1). In the 'random pattern' condition the same reflectances were arranged irregularly. In the 'random colors' condition each background square had a different simulated reflectance. In the 'grey background' condition the background had a uniform achromatic reflectance. The space averaged simulated reflectance of all the background conditions was the same.

The illumination

The simulated scene was always illuminated by a distant lamp (ambient illumination) and a near lamp (simulated to be 40 cm above the surface, 7 cm from the left and upper borders of the screen). We had two illumination conditions: one more or less natural illumination condition combining 1931 CIE standard illuminant C as a distant lamp with CIE standard illuminant A as a local lamp (shown in Figure 1), and a second condition with a green (x= 0.38, y= 0.33) distant lamp and a red (x=0.30, y=0.40) local lamp. The simulated local illumination caused a gradient of luminance and chromaticity across the screen. We used two different ratios between the intensities of the two sources of illumination: a bright local lamp (the luminance directly under the lamp is 166% higher than the ambient value; Figure 1) and a much dimmer local lamp (the luminance directly under the lamp is only 37% higher than the ambient value).

The test & reference disks

A 1 degree diameter reference disk was presented at the top left corner (see Figure 1). Its reflectance was chosen so that the light that reached the eyes from that surface had a luminance of 12.5 cd/m^2 and a chromaticity of [x= .317, y= .367], [x= .350, y= .367] or [x= .333, y= .333]. Subjects adjusted the luminance and chromaticity of a 1 degree diameter test disk at the bottom right to appear to have the same hue and brightness as the reference disk. They could vary the test disk's hue (within the part of the two-dimensional 1931 CIE color space that we could render on the monitor) by moving a computer mouse. They could increase or decrease the luminance by pressing the arrow keys of the computer keyboard. Subjects indicated that they were content with the set value by pressing the mouse button. Once they did so, a new stimulus appeared. The initial hue and luminance of the test disk was determined at random from within the range that could be set.

Subjects

Two authors (JG and JS) and six naïve subjects each took part in a session with the bright lamps and then in a session with the dim lamps. All subjects had normal color vision as tested with Ishihara color plates (Ishihara, 1969). In each session subjects dark-adapted for 10 minutes and then made 5 settings for each combination of the 3 reference reflectances; 4 background conditions and 2 illumination conditions. The 120 settings within a session were presented in random order.

Analysis

We first determined the median (x, y) and the median luminance values of each subject's setting for each of the eight experimental conditions and three different references. A total of 24 median values were calculated for each session per subject. We defined a color induction index as the difference between the set color of the test disk and the color of the reference disk, as a percentage of the difference that we would expect if subjects attributed all differences in the background to differences in illumination; perfect color constancy. So 100% indicates a perfect reflectance match and 0% indicates a perfect match between the light from the test and reference disks (no chromatic induction). The differences were expressed as distances in CIE color space. Only the component of the differences in the direction that would give perfect color constancy were considered. We defined a luminance induction index as the difference between the set luminance and the reference, as a percentage of the difference that we would expect if subjects had attributed all differences in the background luminance to differences in illumination. We averaged the induction indices across the three references to obtain mean induction indices for each subject, for each of the 16 experimental conditions. Repeated measures analyses of variance were used to evaluate the influence of the within-subjects factors 'background condition', 'illuminant condition' and 'illuminant ratio'.

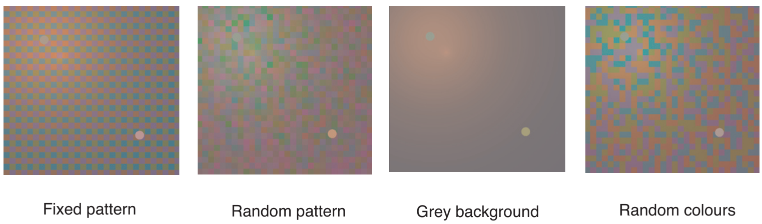

Figure 1:
The four kinds of background illuminated by standard illuminants C (ambient illumination by an overcast sky) and A (a tungsten filament lamp near the top left corner).

Results

The overall average index of chromatic induction was only 10%. The overall average index of luminance induction was 55%. A significant effect of the background condition was found on both chromatic induction ($F_{1,3}=11.01$; $p<0.01$) and luminance induction ($F_{1,3}=25.54$; $p<0.01$). The magnitude of the chromatic induction was larger and that of luminance induction was smaller for the grey background than for the other three background conditions (see figure 2). The chromatic ($F_{1,1}= 30.06$, $p<0.01$) and luminance ($F_{1,1}=64,40$; $p<0.01$) induction were both significantly smaller for the dim lamp than for the bright lamp (18% versus 1% for color and 67% versus 43% for luminance). For luminance induction, there was also an interaction between the factors background condition and illuminant ratio ($F_{1,3}=9.59$; $p<0.01$). Luminance induction was particularly weak with the dim lamp for the grey background condition. A significant main effect of illuminant condition was found for luminance induction ($F_{1,1}=6.40$; $p<0.05$), but not for chromatic induction. The luminance induction was higher for the A-C illuminant condition than for the red-green illuminant condition.

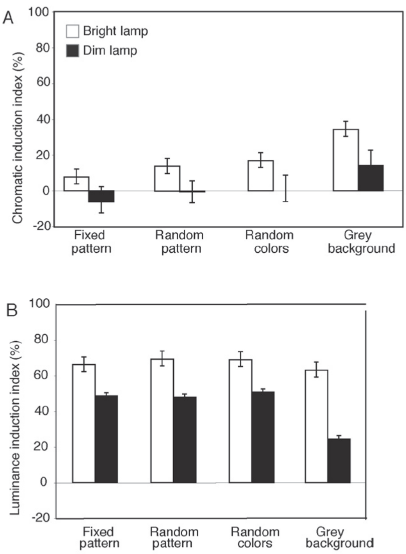

Figure 2: Overall average chromatic (A) and luminance (B) induction for each of the four background conditions, for the bright (white bars) and dim (black bars) lamps. Bars show averages across 8 subjects, 3 references and 2 illumination conditions. Error bars show the Standard Error between subjects.

Conclusions

Our attempts to obtain a high level of chromatic induction by recruiting mechanisms designed to achieve color constancy (Blackwell & Buchsbaum, 1988) clearly failed. The level of chromatic induction was similar to that in simple displays, where there is no reason to believe that the different surfaces are under different illuminations (Shevell & Wei, 1998; Brenner & Cornelissen, 2002; Brenner, Ruiz, Herraiz, Cornelissen & Smeets, 2003). The only clear effect of the background was that there was less induction with more chromatic variability, which has been demonstrated before (Brenner & Cornelissen, 2002). A possibly important difference between our study and the studies that have shown near perfect color constancy in real scenes (Kraft, Maloney & Brainard, 2002; Brainard, Brunt & Speigle, 1997; Brainard, 1998; De Almeida, Fladeiro, Nascimento, 2004), is that we have an 'unexplained' transition at the borders of the screen. We also presented a single (patterned) surface and our subjects were fully aware that they were judging emitted rather than reflected light. We cannot tell which, if any, of these factors is important (Kraft, Maloney & Brainard, 2002; Brainard, Brunt & Speigle, 1997; Brainard, 1998; De Almeida, Fladeiro, Nascimento, 2004), but we here show that making the difference in background chromaticity in different parts of the scene consistent with a realistic gradient in illumination has very little -if any- effect on chromatic induction.

4
Colour constancy is not based on estimating the colour of the illumination

Submitted as:
Granzier JJM, Brenner E, & Smeets JBJ.
Colour Constancy Is Not Based On Estimating The Colour Of The Illumination.

Abstract

Objects hardly appear to change colour when the spectral distribution of the illumination changes: a phenomenon known as colour constancy. Colour constancy could either be achieved by relying on properties that are insensitive to changes in the illumination (such as spatial colour contrast), or by compensating for the estimated chromaticity of the illuminant. We examined whether subjects can judge the illuminant's colour well enough to account for their own colour constancy. We found that subjects were very poor at judging the colour of a lamp from the light reflected by the scene it illuminated. They were much better at judging the colour of a surface within the scene. We conclude that colour constancy must be achieved by relying on relationships that are insensitive to the illumination, rather than by directly judging the colour of the illumination.

Introduction

The light reflected from an object to the eye depends both on the reflectance of the object's surface and on the illumination. The interplay between surface reflectance and illumination produces ambiguity in the retinal image; many combinations of reflectance and illumination give rise to the same light on the retina. One is frequently only interested in the surface reflectance, so the visual system attempts to discount the contribution of the illumination to produce a stable perceptual representation of the object's surface reflectance. This ability is known as colour constancy.

The hypothesis that states that the visual system estimates the illumination of a scene and uses this estimate to determine the reflectance of surfaces of interest is known as the 'Illuminant Estimation Hypothesis' (Koffka, 1935; Beck, 1972; Epstein 1973). Many computational theories of colour constancy (e.g., Buchsbaum, 1980; D'Zmura & Lennie, 1986; Brainard &

Freeman, 1997) are based on this hypothesis. An obvious strategy for estimating the illuminant's colour is by analyzing the light from the illuminant itself. However, the illuminant is often not directly visible, or too bright to estimate directly, so one will often have to rely on less direct sources of information. Assumptions about the way in which the visual system infers the colour of the illumination include the assumption that the average reflectance of the whole scene is grey (Buchsbaum, 1980, but see Granzier et al., 2006) or that the brightest surface is white (Land & McCann, 1971). The correlation between colour and luminance within the scene may also help to estimate the illuminant (Golz & MacLeod, 2002; but see Granzier et al., 2005). Obviously, these assumptions are not always correct, but there need not be a single principle for estimating the illumination. Relying on a combination of assumptions could provide a robust judgment of the illuminant.
Knowing the colour of the illumination may be of interest to the visual system, for instance for estimating the time of day or

Figure 1: The same scene illuminated by two different lamps.

predicting the weather (Zaidi, 1998, Jameson & Hurvich, 1989; Lotto & Chittka, 2005). We are able to differentiate morning light from noon light and tungsten light from fluorescent light, even if the illuminants themselves are invisible. The fact that people are aware of the illumination is evidence against the hypothesis that all information regarding the illuminant is automatically discarded early in visual processing.

The Illuminant Estimation Hypothesis predicts that if subjects are good at estimating the illuminant's colour, they will also be good at estimating surfaces' colours (i.e. they will exhibit high amounts of colour constancy). If subjects are poor at estimating the illuminant's colour they will be poor at estimating surfaces' colours. Systematically incorrect estimates of the illuminant will result in systematic patterns of errors in subjects' surface colour estimates. Brainard and colleagues (Speigle & Brainard, 1996; Brainard, Brunt & Speigle, 1997) have shown that the patterns of errors in surface colour estimation are consistent with incorrectly estimating the scene illumination and then discounting the illuminant using this incorrect estimate (i.e. they can be described by an 'equivalent illuminant'). However, one could also obtain colour constancy without estimating the illumination; by relying on illuminant-independent strategies (e.g., Land, 1977). Such mechanisms need not be perfect. Perceiving the illuminant's colour could be a (useful) manifestation of an imperfection in colour constancy. Judging the degree of ripeness of fruit in a tree does not really require very exact information about surface reflectance, so small errors could be tolerated.

Given the fact that the Illuminant Estimation Hypothesis has been around for so long, it is surprising to see how few attempts have been made to test it. Several studies (Linnell & Foster, 2002; Khang & Zaidi, 2004) claimed to investigate illuminant colour perception, but they compared similar scenes under different illuminants, rather than having people report about the illuminant itself. The Illuminant Estimation Hypothesis has been studied more extensively in the lightness domain (e.g. Rutherford, 2000; Rutherford & Brainard, 2002; Logvinenko & Menshikova, 1994; Gilchrist & Jacobsen, 1984).

If estimating the illuminant is essential for obtaining colour constancy, we should find a clear relationship between how well people can judge the illuminant's colour and the level of colour constancy. If the Illuminant Estimation Hypothesis is incorrect, and the visual system uses illuminant-independent strategies to achieve colour constancy, there need not be a relationship between colour constancy and judgments of the illuminant's colour. We therefore set out to test how well subjects can estimate the illuminant's colour and whether their colour constancy is consistent with this estimate.

General Methods

Subjects

Seven subjects took part in the two experiments. They had normal colour vision as tested with Ishihara colour plates (Ishihara, 1969). One subject was an author (J.S). The other subjects were naïve as to the purpose of the experiment. This research is part of an ongoing research program that has been approved by the local ethics committee.

The lamps

The lamps were presented one at a time in random order. The luminance (as measured with a Minolta CS-100A chroma meter) was set so that the light reflected from a white piece of paper at the center of the experimental scene was 24 cd/m^2 for all lamps. This was achieved by manipulating the voltage of the input to the lamps. Four different lamps were used to illuminate the scene. The CIExy coordinates of the light from these lamps were (0.315, 0.565), (0.461, 0.412), (0.505, 0.448) and (0.513, 0.414). The subjects could not see the lamps and did not know how many lamps there were, or their colours.

The scenes

We used real 3-dimensional scenes and real illuminants to create optimal circumstances for estimating the illuminant's colour (see figure 1). We included smoothly curved and shiny objects of various colours (providing clear highlights; Lee, 1986) and the objects were placed in a manner that gave rise to shadows and mutual illuminations (Drew & Funt, 1990; Bloj et al., 1999). The scene was in front of the subjects, at a distance of 100-250 cm, and was seen through an opening in a black curtain (see figure 2). At any time it was illuminated by one of the four lamps. The lamps had fixed positions. Two lamps were to the left of the scene and two lamps were to the right of the scene. There was a CRT monitor to the right of the scene, in front of the curtain, 100 cm from the subject. The walls of the room were black.

We are quite good at remembering objects' colours (Bertuliene & Bertulis, 1991; Sachtler & Zaidi, 1992). Hering (1874/1964) and Helmholtz (1867/1962) proposed that memory

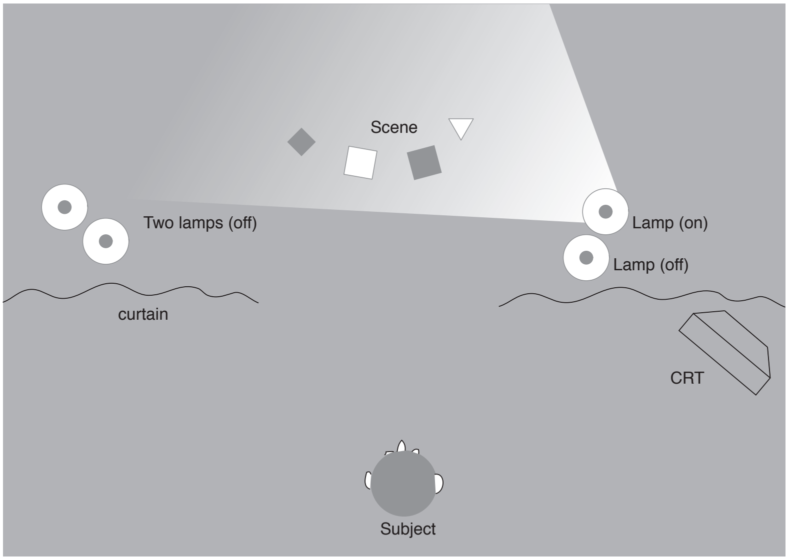

Figure 2: Schematic overview of the set-up. Subjects adjusted the colour of a disk on the CRT to match the colour of the light from each of the four lamps. A curtain separated the scene from the monitor.

of the colours of objects could help achieve colour constancy, and object familiarity has indeed been found to improve colour constancy (Hansen, Olkkonen, Walter, & Gegenfurtner, 2006; Hurlbert & Ling, 2004; Ling & Hurlbert, 2006; Jin & Shevell, 1996), although the effects are quite small. In order to determine whether objects of which the reflectance is known help in estimating the illuminant's colour we used two scenes; one with objects of which the colours are known (objects with object specific or brand specific colours; figure 3) and one with objects that have an unknown colour (objects that can be bought in many colours; figure 3).

Illuminant Estimation

The first step was to determine how well subjects could judge the colour of the illumination. Subjects had to set the colour of the light from a disk at the centre of a calibrated Sony GDM-FW 900 Trinitron monitor (48 cm x 31 cm; 1920x 1200 pixels; 90 Hz; 8 bits per gun) to match their estimate of the colour of the lamp. The disk on the monitor had a diameter of 3.5cm (about 5 deg). Its luminance was 10 cd/m^2. The rest of the screen was dark. We used a single surface on a screen to ensure that there could be no confusion about this being emitted light.

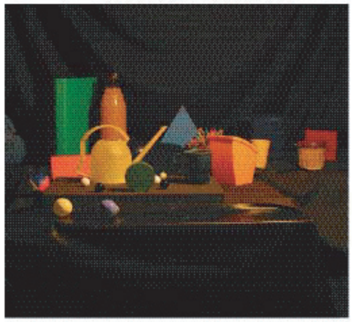

Figure 3: Scenes with objects with known (left) and unknown (right) colours.

Procedure

Subjects could vary the colour of the adjustable disk within a two dimensional CIE isoluminant colour space by moving the computer mouse. They indicated that they were content with the match by pressing a button. Once they did so, the lamp was switched off and shortly afterwards a new lamp was switched on. The initial colour of the adjustable disk was chosen at random from within the range that could be rendered with our equipment.

After adapting for 5 minutes to the relatively low room illumination with one of the lamps, each subject made matches for 40 minutes. Depending on how fast they were, this gave 8-17 matches per lamp. The lamps were presented in random order.

Subjects performed the estimation task twice, in two sessions; one with 'objects with known colours' and one with 'objects with unknown colours'. The order of the sessions was counterbalanced across subjects.

Results & Discussion

We determined the mean CIExy coordinates of each subject's matches for each of the four lamps. Figure 4 shows the average coordinates for each lamp with their standard errors (across subjects). The coordinates of the light from each of the lamps are also shown. Inspection of figure 4 shows that the matches were clearly different for the different lamps, but subjects consistently underestimated the saturation of the light from the lamps. There was considerable variability within individual subjects' estimates for each lamp: average standard devia-

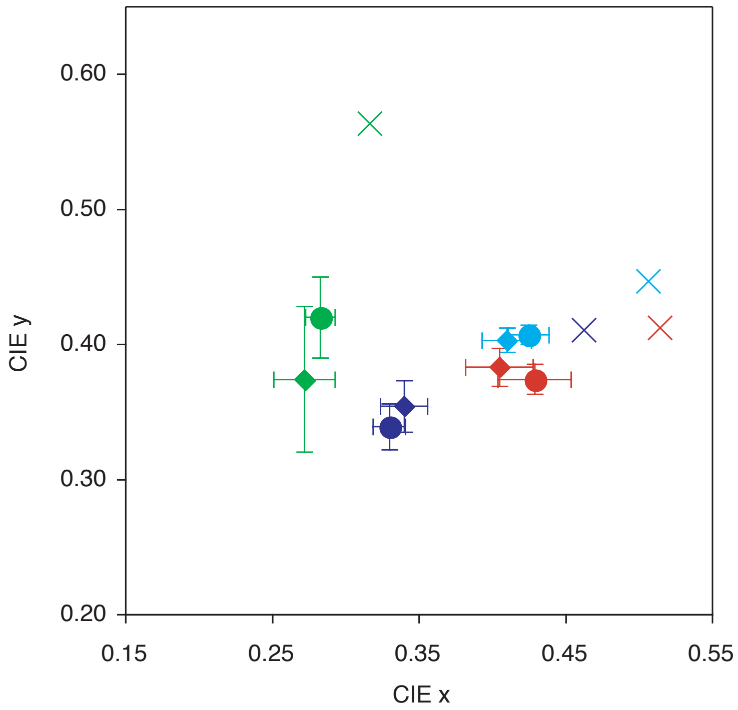

Figure 4: Estimates of the colour of the lamps in the presence of objects with known colours (disks) or with unknown colours (diamonds). Each symbol shows the mean of the subjects' average matches for one lamp (indicated by the different colours). The correct values are indicated by the crosses.

tions of .078 and .064 for the x and y coordinates respectively. Illuminant colour estimation was not much better in the scene with objects that have a known colour than it was for the scene in which the objects do not have a known colour (compare disks with diamonds).

Colour Constancy

Our next step was to see whether surface reflectance is judged just as poorly. Since we did not find any real difference between the two scenes, we only used the scene with 'known colours' for our colour constancy experiment.

Procedure

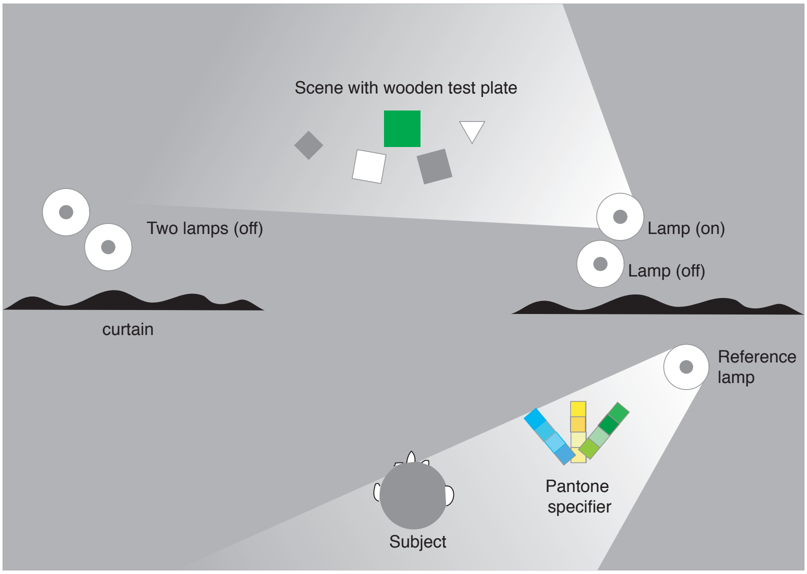

Figure 5: Schematic overview. Subjects selected the sample from the colour selector that best matched the wooden test plate. The pantone selector was illuminated by a reference lamp. The scene with the wooden test plate was illuminated by the same lamps that were used when estimating the colour of the illumination.

Subjects selected the sample of a pantone professional colour selector (Pantone Inc, New Jersey, USA) that best matched the surface of one of three wooden test plates (the number of plates was unknown to the subjects and only one was visible at a time; see figure 5). The wooden test plates were placed within the scene containing 'objects with known colours' (see figure 6). We used the same four lamps that were used in the "illuminant estimation" part of the experiment. The scene was illuminated by one of these four lamps at a time. The pantone samples were illuminated by the reference lamp, which was very similar to one of the lamps: (0.452, 0.411). Subjects were instructed to indicate the colour in which the wooden test plate had been painted.

The test plates

The CIExy colour coordinates of the light reflected by the three wooden test plates under the reference lamp are: (0.308, 0.354), (0.444, 0.470) and (0.387, 0.516). Thus, for perfect

Figure 6: The scene with one of the three test plates as seen from the subjects' vantage point.

colour constancy subjects should select the sample that reflects light with these coordinates. The painted wooden plate was placed in the middle of the scene, always at the same location and with the same orientation with respect to the observer. The three wooden test plates were each illuminated by each of the four lamps of the illuminant estimation experiment, giving a total of 12 combinations of surface and illumination. Each combination was presented three times, in random order, leading to a total of 36 matches for each subject. This colour constancy experiment took about 90 minutes (per subject).

Analysis

The first step was to measure the colour coordinates of each of the chosen pantone samples when illuminated by the reference lamp. We will call these values subjects' 'actual matches'. We determined the mean coordinates of each subject's matches for each of the twelve experimental conditions. We then averaged these coordinates across subjects and calculated the associated standard errors. A total absence of colour constancy would mean that subjects match the colour of the light that reaches their eyes. We will refer to such a match as a 'match of reflected light'. Perfect colour constancy would be achieved if subjects totally discounted the colour of the illuminant so that their matches are independent of the lamp. The chosen paper would reflect the same light as the test plate under the lamp illuminating the pantone selector. We will refer to a perfect match of the surface reflectance as a 'correct match'. If the Illuminant Estimation Hypothesis is correct, we should find a correlation between how good subjects are at estimating the illuminant and how accurately they match the reflectance of the wooden test plates. We therefore determined the deviations of subjects' illuminant matches from the correct matches (distances in CIExy) and the deviations of subjects' matches for the wooden test plates from the correct matches, and calculated correlation coefficients between both deviations (across subjects).

Finally, we determined how we could expect subjects to match the surfaces considering the misjudgments of the illuminants in the first part of the study. We assumed that the colour of the direct light from the monitor, as matched in the first part, directly represents the colour that subjects use to estimate the wooden test plate's reflectance from the light that it reflects. However, considering how poorly subjects judged the colour of the lamp illuminating the scene we can expect subjects to also

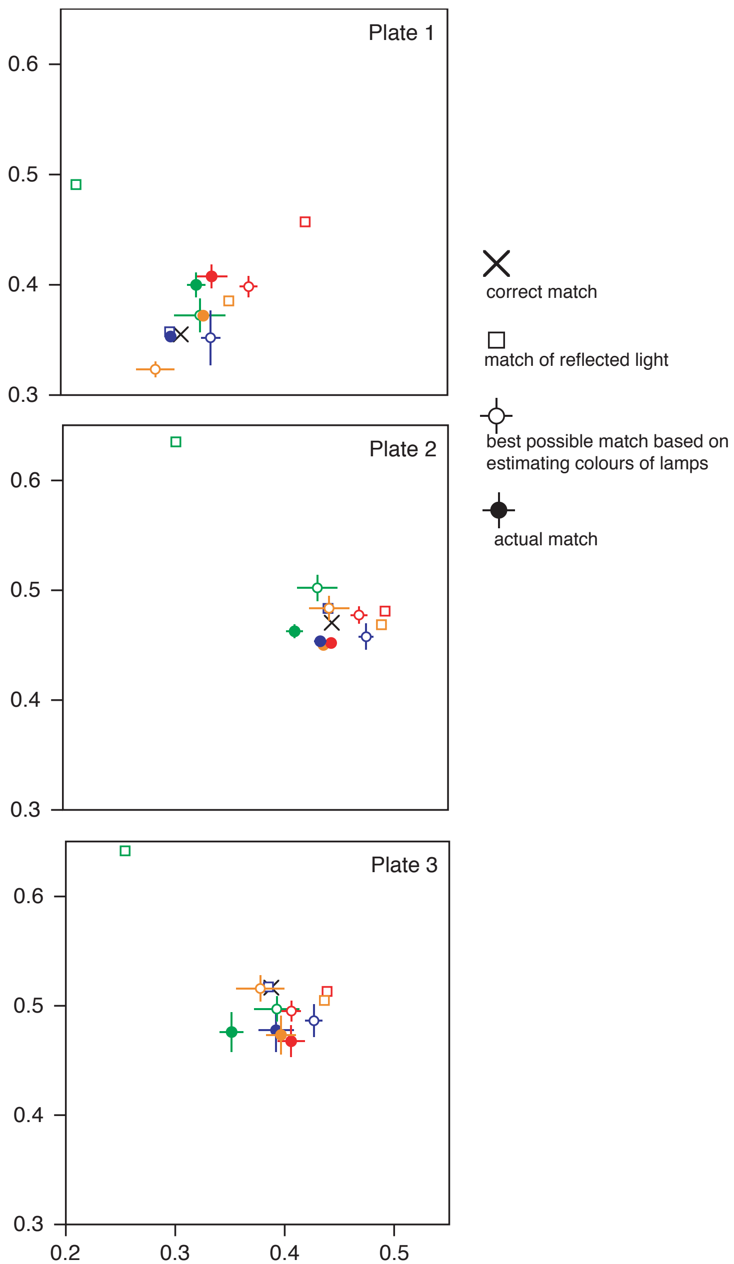

Figure 7: Estimates of surface reflectance. Matches for each of the three wooden test plates (panels) and four experimental illuminants (each represented by a different colour). Closed disks: mean actual matches with standard errors across subjects' mean values. Squares: matches of reflected light. Crosses: correct matches. Open disks: best possible match based on estimating colours of lamps, with standard errors based on the variability between subjects.

misjudge the colour of the lamp illuminating the pantone colour selector when making the match. We therefore determined the value that would best account for the data by minimizing the summed square distance in 1931 CIExy colour space be-tween the actual matches and the prediction. We did so for each subject and than averaged these values. We will refer to the prediction based on this fit as the 'best possible match based on estimating colours of lamps'. Performing this fit is comparable with finding the most likely 'equivalent illuminant', as described in the introduction.

Results & Discussion

Figure 7 shows the mean actual matches averaged across subjects for each wooden test plate and lamp. Also shown are the matches of reflected light, correct matches and the best possible match based on estimating colours of lamps. The actual matches lie very close to the correct matches (far from the matches of reflected light). Thus, colour constancy is much better than one would predict from the poor estimates of the colour of the illumination (shown in figure 4).

The average within subjects standard deviations for the matches, in terms of distance in 1931 CIExy, were .057 and .052 for the x and y coordinate, respectively. Thus, there was slightly less variability in colour matches for the wooden test plates than there was for estimating the illuminants. The mean correlation between how well subjects performed on the two tasks (across tasks and lamps) was .02 with a standard deviation of .38.

Even the best possible match based on estimating colours of lamps cannot account for the actual matches: the systematic errors (relative to a correct match) cannot be accounted for by a single systematically misjudged colour of the lamp. The CIExy coordinates for our fitted lamp are almost identical to those of the similar lamp illuminating the scene: (0.365; 0.037); (0.336 ± 0.037; mean ± SD), but this cannot be considered as support for the Illuminant Estimation Hypothesis, because it must be so if surface reflectance is judged more or less correctly (due to the way we fit the data).

General Discussion

We can clearly reject the strong version of the Illuminant Estimation Hypothesis. Subjects are not good at estimating the illuminant's colour whereas their surface colour estimates are quite accurate. Moreover, there was no correlation between how well subjects could estimate the colour of the lamp and how well they could estimate the colour of the surface.

A weaker version of the Illuminant Estimation Hypothesis, whereby subjects' judgments are based on an estimate of the illuminant but the latter can be quite incorrect, is more difficult to reject. Our reason for also considering the weaker version to be unlikely is that even finding the hypothetical misjudgment of the illumination of the pantone selector that best fits the data does not reproduce the errors that are made. Of course, one could argue that the colour of the test plate (and of the selected sample) influence subjects' estimates of the illumination. However, if so then the Illumination Estimation Hypothesis is little more than an alternative description of the results, because any error in judging a surface's colour can be interpreted as a misjudgment of the illumination. Regularities in such errors could be attributed to systematic errors in judging the illumination, but they could just as easily be attributed to mechanims such as simultaneous or successive colour contrast. Thus, being able to describe the data in terms of an equivalent illuminant (Speigle & Brainard, 1996; Brainard, Brunt & Speigle, 1997) is not enough to conclude that such an illuminant is really estimated.

Our results complement recent results showing that improving information about the illuminant does not necessarily help to judge surface colours (Amano et al., 2006; Amano et al., 2005). That subjects' estimates of the illuminant's colour were so poor in the first part of our study is remarkable, because subjects could have used specular highlights that were abundant in our experimental scene. Highlight can give direct information about the chromaticity of the illuminant (Lee, 1986; D'Zmura & Lennie, 1986). However, the highlights in our experimental scene always looked “whitish” (desaturated) as a result of the high luminance (‘Bezold-Brücke hue shift’; Nagy & Zacks, 1977). This may explain why subjects estimated the colour of the illuminants to be more desaturated (although we presented an alternative explanation in the introduction; a partial failure of colour constancy).

Helmholtz (1867/1962) proposed that the illuminant component in the light reaching the eyes is judged by making unconscious inferences based on past experience. In our task, subjects had to judge the illuminant's colour by making conscious, explicit estimates. Thus, it could be that the Illuminant Estimation Hypothesis holds at an unconscious level that is impenetrable

Figure 8: Would you have thought that the sun is so orange (mirror reflection in tall building) if you had only seen the lower buildings? Does this influence how you see the white surfaces?

to empirical study. We here show that if the visual system uses an estimate of the colour of the illuminant in order to achieve colour constancy, it does not use the colour that is judged at a conscious level. If estimation of the illumination occurs at an unconscious level, the question is how detailed the analysis of the illumination is, because a very simple unconscious judgment, such as taking the average chromaticity of a scene as an indication of the illuminant's chromaticity, can just as well be interpreted as relying on invariant properties of a scene to obtain colour constancy.

Conclusion

We show that judgments of surface colour do not rely on estimating the colour of the illumination. An illustration of this phenomenon is shown in figure 8.

5
A Direct Test Of The 'Grey World Hypothesis'; A Comparison Of Different Matching Methods

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Abstract

Many of the proposed ways in which the visual system could disentangle influences of illumination from influences of reflection on the colour of the light that reaches our eyes, are implicitly or explicitly based on the assumption that the average reflectance of our environment is grey; the 'Grey World Hypothesis'. Here we investigate whether subjects make large errors when this assumption is not true. Subjects performed matching tasks in which they matched the colour and luminance of a test plate, either by setting the colour of an adjustable patch on a monitor or by selecting a sample from a large set of printed colour samples '(Pantone Colour Specifier)'. Matches were made with the test plates embedded in scenes either containing only red or only green objects. Matches hardly differed between the red and green scenes. Thus, the average colour of the scene cannot be the primary scene statistic underlying colour constancy. We found that the matches were most consistent both across and within subjects when using the Pantone Specifier.

Introduction

Because the light reflected from an object to the eye depends both on the object's surface reflectance and on the illumination, and the observer is usually only interested in the former, the visual system needs some way to compensate for changes in the illumination (Helmholtz, 1867/1962). To accomplish this, the visual system is likely to consider the light coming from other surfaces (Land & McCann, 1971). If the illumination of a scene changes so that there is more energy at long wavelengths, the light reflected from all surfaces changes correspondingly, so that the chromaticity averaged over the entire image becomes more reddish. A simple approach to colour constancy could therefore be to take the space averaged chromaticity as a measure of the chromaticity of the illumination. Doing so is based on the assumption known as the 'Grey World Hypothesis' (Buchsbaum, 1980). It could easily be implemented early in the visual system as a cone-specific multiplicative gain control (von Kries adaptation) (Von Kries, 1905), which either extends across the retina (Helson, 1934) or is spread spatially through eye movements (Cornelissen & Brenner, 1995). Relying exclusively on transitions at borders (Land & McCann, 1971) also indirectly relies on the Grey World Hypothesis. There is no general agreement about the status of the Grey World Hypothesis in colour constancy; several studies find that the average background colour influences illu-

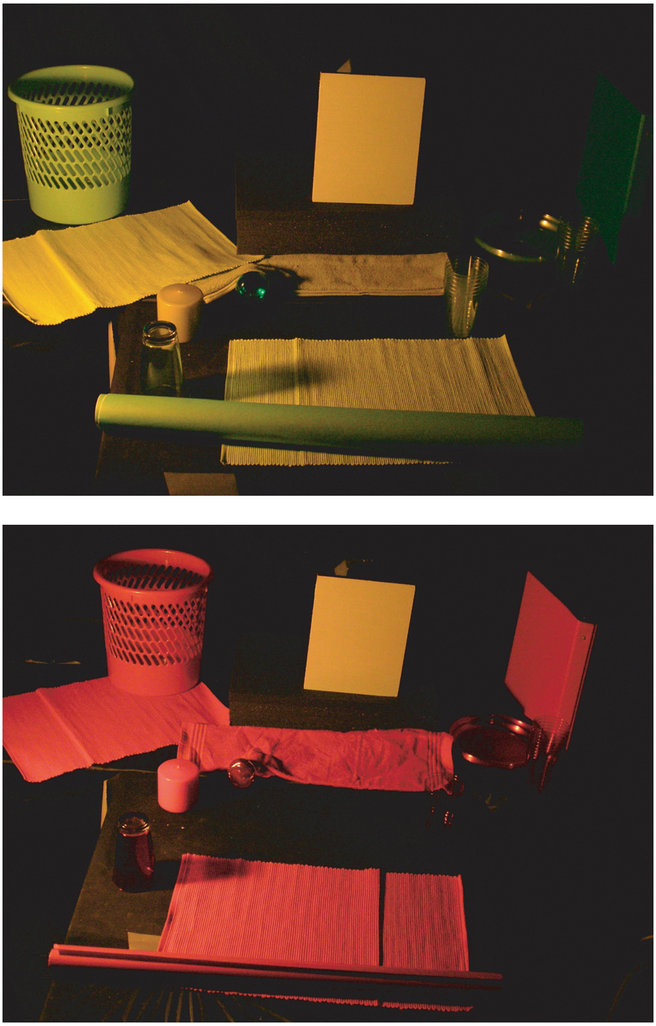


figure 1: An impression of the objects used for the 'green scene' condition (top) and the 'red scene' condition (bottom) of experiment 1. One of the two test plates is shown at its position at the back of the scene.

minant colour estimation consistently (Khang & Zaidi, 2004; Linell & Foster, 2002), while others do not (Yang & Maloney, 2001; Kraft & Brainard, 1999; Rutherford, 2000; Brainard & Wandell, 1986). Most studies (Khang & Zaidi, 2004; Linell & Foster, 2002; Yang & Maloney, 2001; Brainard & Wandell, 1986) that examined the influence of the average chromaticity in the scene used virtual scenes. It is not certain that such data can be generalized to real surfaces and real illuminants (Brainard, Rutherford & Kraft, 1997).

The Grey World Hypothesis obviously must lead to large errors in colour judgment if the visual background mainly contains surfaces of a certain colour (blue sky, green leaves, red brick houses) (Brown, 1994; Webster & Mollon, 1997). We here examine whether colours are indeed misperceived under such conditions.

Experiment 1

Methods

Scene

In order to manipulate the average colour of the scene independently of local contrast, test plates were placed in front of a very dark background, with coloured objects at a distance from the test plate that ensured that they were separated by at least 1.37 deg. They were common household objects (waste paper basket, towel, cup, etc) that we could obtain in both colours. We used ten objects for each scene. Subjects sat 250 cm from the test plates, and 200 cm from the nearest of the surrounding objects.

We used two scenes: one with only green objects and one with only red objects (figure 1). We will refer to the former as a 'green scene', although actually only the objects were green. We will refer to the scene with red objects as a 'red scene'. If people rely on some version of the "Grey World Hypothesis" to deal with changes in illumination, we expect subjects' matches of the colour of the test plates to be shifted substantially towards 'red' when the plates are presented amongst green objects and to be shifted towards 'green' when the plates are presented amongst red objects. There were only two test plates, and they were both used in all conditions. However subjects were not aware that there were only two test plates, even after running the experiment. Under daylight illumination, one plate looked orange and the other looked green (both of low saturation).

Lamps

In order to be able to estimate the magnitude of colour constancy, and to make it clear to the subjects that biases could be due to the illumination, we used two different lamps to illuminate the scene. Only one lamp was on at a time. Its brightness was set (by manipulating the voltage driving the lamps) so that the light reflected from a white piece of paper at the centre of the experimental scene was 25 cd/m^2. The lamps had 1931 CIE x, y coordinates of (0.514, 0.412) and (0.485, 0.413) as measured directly with a Minolta CS-100A chroma meter after the voltage driving the lamps had been set. The lamps were positioned between the subject and the scene, slightly to the left of the subject, and were hidden from view at all time.

Matching Conditions

We asked subjects to match the surface in two ways: by selecting the matching surface from a Pantone Colour Specifier (Pantone, 1984) (figure 2a) and by setting a colour on a CRT (see figures 2 b-d). The matching stimulus (the Pantone Specifier under a lamp or an image on a CRT) was presented in another part of the room. When setting the colour (and luminance) on the CRT we had good control of the surrounding image, but there is no real distinction between reflectance and illumination, so subjects could interpret the task as to match the light coming from the two surfaces. For the Pantone Specifier the contribution of surface reflectance is clear, but we have little control of the surrounding. We therefore used both the Pantone Specifier and the

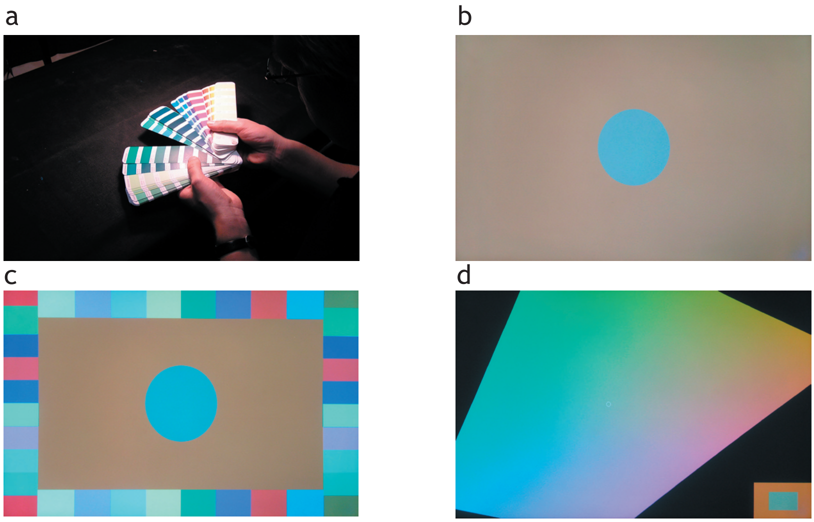


Figure 2: The four matching stimuli used in experiment 1. The Pantone Colour Specifier (a), The simple matching stimulus (b), The stimulus with saturated colours (c) and the visualized CIE matching stimulus (d).

CRT and compared the results.

The Pantone Specifier

The Pantone colour specifier was illuminated by a 'reference lamp' (0.456, 0.413) that was very similar to one of the two lamps illuminating the scene. It was set to reflect 25 cd/m^2 to the subject's eye when a white piece of paper was placed at the position at which subjects held the Pantone Specifier. Under this lamp the two test plates reflect light with coordinates (0.446, 0.430) and (0.485, 0.416). Subjects had to select the sample from the Pantone Colour Specifier that best matched the paint of the test plate. They were free to leaf through the "pages" until they found a suitable sample.

CRT images

The CRT screen (a calibrated Sony GDM-FW 900 Trinitron monitor, 48 cm x 31 cm; 1920 x 1200 pixels; 90 Hz; 8 bits per gun) was 100 cm from the subject. Subjects had to match the colour and luminance of a part of the screen to the colour and luminance of the test plate. The part's chromaticity was manipulated (within the part of the CIE colour space that we could render on the monitor) by moving the computer mouse. Subjects could set the luminance by pressing the arrow keys of the computer keyboard. They indicated that they were content with the set value by pressing the mouse button. The initial hue of the adjustable patch was determined at random from within the range that could be set for each match. The luminance of the adjustable patch was 10 cd/m² for the first match, but it remained at whatever value the subject set on the next trial. In the 'simple matching condition' (see figure 2b) there were only two colours on the screen: the colour set by the subject (within a 5 deg diameter disk at the center of the screen) and a uniform background (10 cd/m²) with the same coordinates (0.47, 0.42) as the light from the "white" background of the Pantone colour specifier (when illuminated by the reference lamp).

We know that the perceived saturation is influenced by the saturation of other colours in the scene (Brenner, Ruiz, Herraiz, Cornelissen & Smeets, 2003; Brown & MacLeod, 1997). When matching surfaces using the Pantone Specifier, the subject is exposed to a wide variety of colours. We therefore also used a CRT matching condition in which a variety of saturated colours

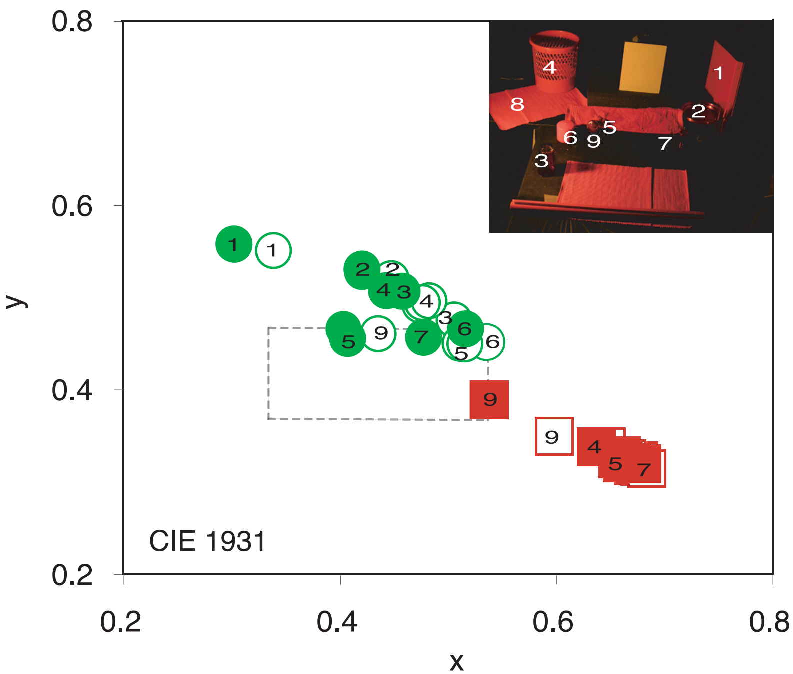


Figure 3: CIE x, y coordinates of the objects found in the 'red scene' (squares) and 'green scene' (circles). The numbers refer to the objects as indicated. The CIE coordinates are given both for lamp 1 (open symbols) and lamp 2 (solid symbols). The dashed rectangle represents the colour space of figures 4 and 6.

surrounded the background (see figure 2c). In this 'saturated colours matching condition', the background on the screen was the same as in the 'simple matching condition', but with saturated colours (mean luminance of 16.9 cd/m^2 with a standard deviation of 8.6 cd/m^2) around the borders of the screen.

Another difference between the Pantone Specifier and a CRT matching task is that with the former the subject can instantaneously choose from the whole colour gamut of matching colours. This is not the case for the two above-mentioned CRT matching conditions. In order to test whether this makes any difference, we displayed a part of the 1931 CIE colour space (x: 0.215-0.465; y: 0.25-0.5; 20 cd/m^2) on a black background on the monitor. Subjects could choose the matching colour by moving a cursor (open white ring) to the appropriate position in this CIE colour space (see figure 2d). All colours within the range that could be rendered on the CRT were visualized. A patch at the bottom right of the screen showed the chosen colour and luminance. The background of the patch had the same colour (0.47, 0.42) and luminance (10 cd/m^2) as the colour and luminance of the background in the 'Simple matching condition'. The luminance of the disk at the bottom right was set by pressing the arrow keys. We will refer to this condition as the 'Visualized CIE' matching condition.

Subjects and Procedure

Six naïve subjects with normal colour vision (as tested with Ishihara colour plates (Ishihara, 1969) participated in the experiment. After dark adapting for 5 minutes, each subject made 12 settings (2 test plates x 2 lamps, each presented 3 times). This was done in a seperate session for each scene and matching condition. Within each session the lamps and test plates were presented in an arbitrary order. The experimenter changed the illumination and test plates manually after a match had been made. The lamps were switched off and a new test plate was set in the scene before the new lamp was switched on.

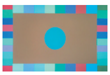
Analysis

We converted the chosen samples of the Pantone Specifier into CIE coordinates by measuring the light that they reflect when illuminated by the reference lamp. We determined each subject's mean CIE (x, y) value for each of the 32 (2 lamps x 2 test plates x 2 scenes x 4 matching conditions) experimental conditions. We then averaged across subjects and calculated the standard errors in these averages. We used these averages to evaluate the influence of the bias in the colour of the surounding due to the selection of objects and to the lamp used to illuminate the scene (figure 3).

Results

Figure 4 shows subjects' average settings for the four matching conditions. The effect of the colour of the scene on subjects' colour matches was quite small (compare squares with circles) and they were often not even really in the expected direction (opposite the direction in figure 3). The difference between the settings under the two lamps was large (compare open and solid symbols), indicating that colour constancy was

Table 1: Standard deviations in matches of experiment 1 (distance in 1931 CIE colour space)

	between subjects		within subjects	
	x	y	x	y
	0.006	0.003	0.006	0.003
	0.019	0.013	0.013	0.008
	0.021	0.018	0.021	0.012
	0.020	0.015	0.016	0.009

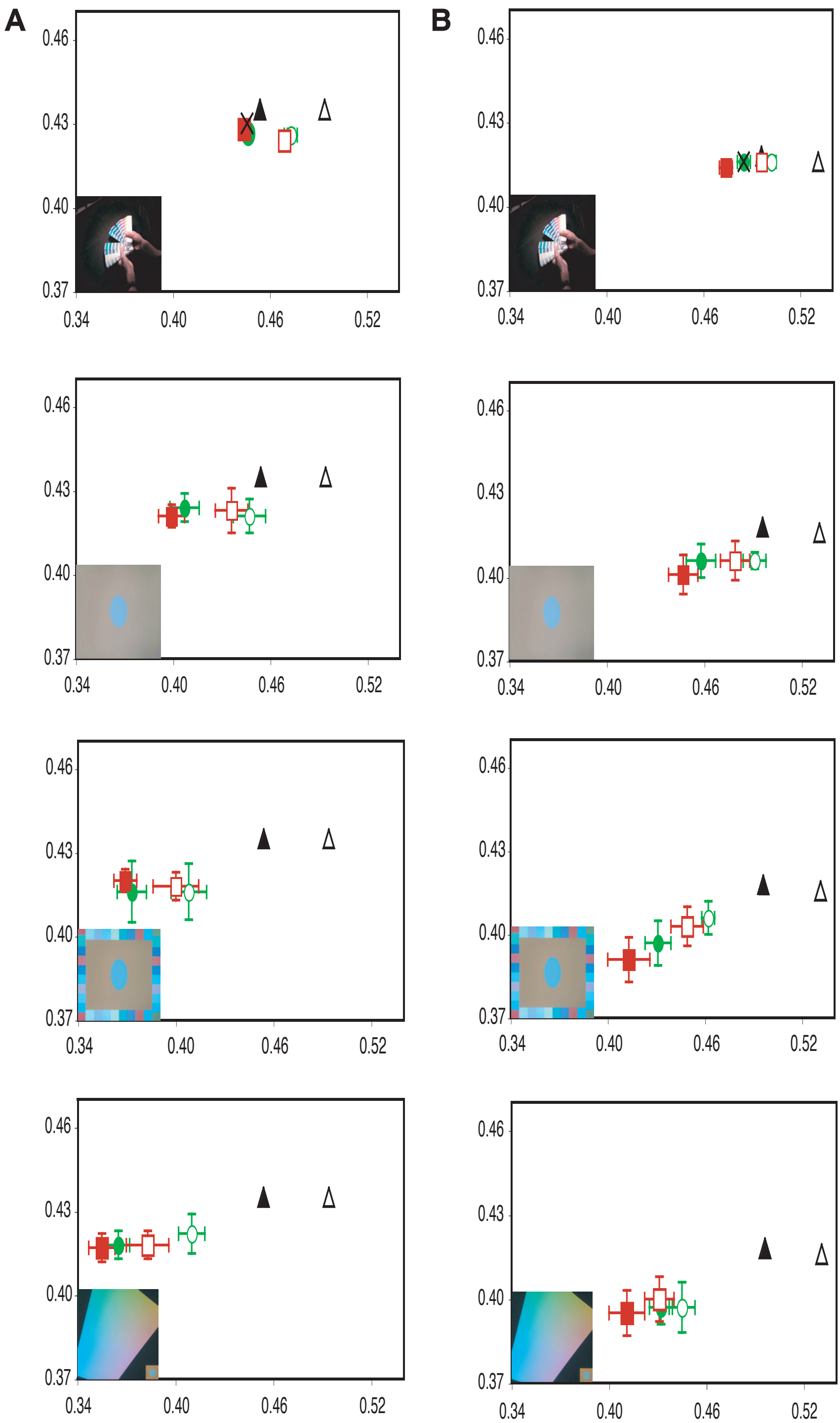


Figure 4: Average colour settings (with standard errors across subjects) for the four matching conditions (see inserts) and two test plates (a, b) of experiment 1. Plots show x and y CIE coordinates on the horizontal and vertical axes respectively. Squares represent matches made for the 'red scene' and circles represent matches for the 'green scene'. Open and solid symbols show data for the two lamps. Triangles show the settings that subjects would have made if they had perfectly matched the light reaching their eyes. The cross (only shown for the Pantone Specifier) indicates the value for perfect colour constancy (obviously independent of the lamp).

poor. However, at least for the samples chosen from the Pantone Colour Specifier, there was clearly a tendency towards colour constancy (for perfect colour constancy all circles and squares would lie on the cross). When matching with an image on a CRT, subjects clearly did not simply match the light reaching their eyes (in which case the squares and circles would coincide with the triangles). Table 1 shows that both the standard deviation between subjects' matches (between-subjects) and the average standard deviations between replications by the same subject (within-subjects) are markedly smaller for the Pantone Specifier than for the CRT.

Discussion

We show that the perceived colour was hardly affected by the fact that the scene only contained objects of a certain colour, so subjects apparently did not rely heavily on the Grey World Hypothesis. At the same time, subjects' matches were quite different for the different lamps, indicating that colour constancy was poor under these conditions (even for the matches with the Pantone Specifier, for which colour constancy can be estimated to be about 50% (Lucassen & Walraven, 1996). Thus the lack of effect of the scene colour was not due to subjects using a more elaborate strategy to achieve colour constancy. A simple explanation of these results could be that local chromatic contrast plays a crucial role in colour constancy, and that our black scene was dark enough (0.40 cd/m^2) to disrupt this source of information (as intended). Moreover, in our experiment only about 20% of the visual field was filled with either green or red objects. The remaining 80% of the visual field was black. It could therefore be that the average colour of both scenes was still too similar. We therefore repeated the experiment, but now covering the whole scene with either red or green fabric. This should increase the influence of the scene both if local contrast plays a critical role for obtaining colour constancy and if the average colour of the scene is important.

We found a clear difference between the matches using the Pantone colour Specifier and those using a computer monitor. These differences were present even though we took care to

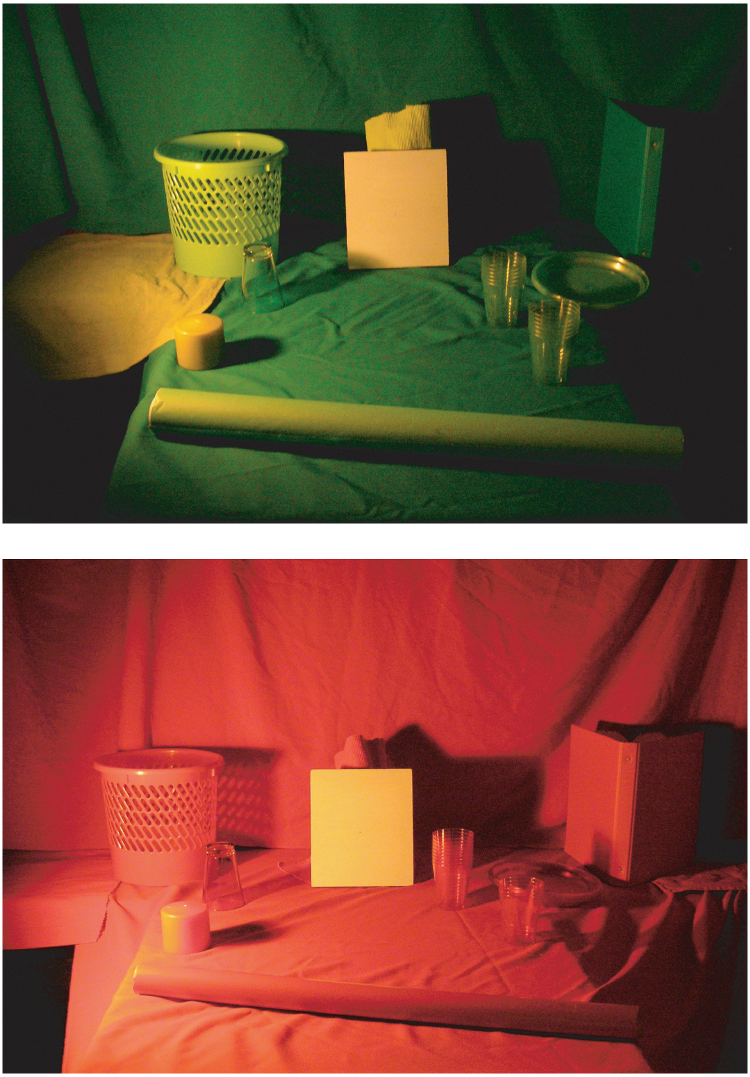


Figure 5:
Scene used for the 'uniform green' (top) and the 'uniform red' (bottom) conditions of experiment 2.

match the tasks in various ways. The conclusion with respect to the Grey World Hypothesis, however, is the same for both tasks. Because the Pantone Specifier showed the most reliable matching data, we only used this matching method in our second experiment.

Experiment 2

Methods

The methods, procedure and analyses were identical to those used for the Pantone Specifier matching condition in experiment 1. The only difference was that we draped a large red or green cloth across the whole scene. We will refer to the scene in which everything was green or red as the 'uniform green' and the 'uniform red' scene respectively. We used the same red and green objects, positioned at roughly the same locations as in experiment 1 (see figure 5). The same two lamps and two test plates of experiment 1 were used. The same six subjects also participated in experiment 2.

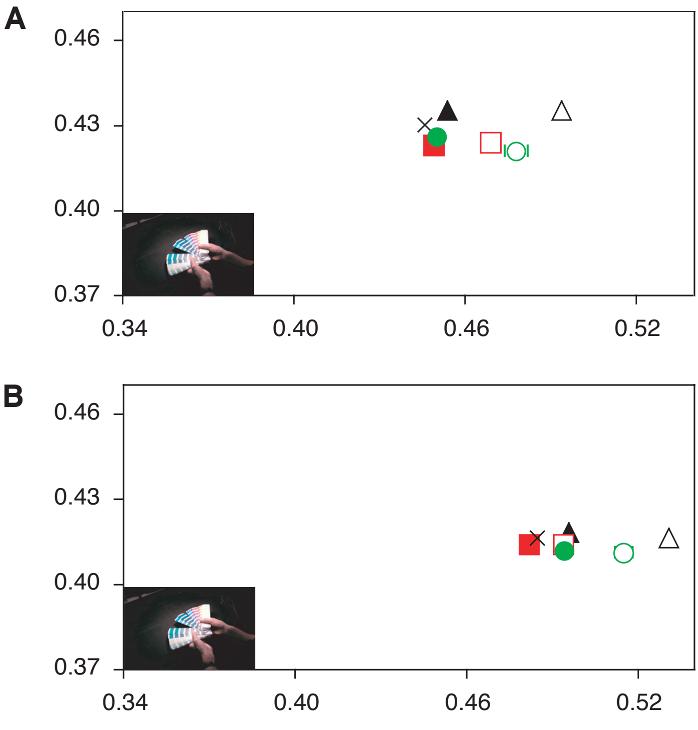


Figure 6: The top and bottom figures show the means and standard errors (mostly smaller than the symbols) of the matches made for the two test plates in experiment 2. For further details, see figure 4.

Results

The results are shown in figure 6. Filling the whole scene with one colour hardly made a difference (compare figure 6 with the upper row of figure 4). There was still only a very small difference between matches for the red and green scenes (compare squares with circles). Colour constancy was also still far from complete: subjects' matches clearly depended on the illumination (compare open and solid symbols).

General Discussion

Even when we filled the whole scene with either green or red surfaces, the bias in subjects' colour perception was very modest. The Grey World assumption predicts a very large effect: corresponding with the differences between the colours shown in figure 3 (note that figures 4 and 6 only show the region within the dashed rectangle in figure 3). This could imply that the visual system managed to recognize the fact that the objects were biased in chromaticity, rather than the differences arising from differences in illumination. The information with which to do so is available from highlights, shadows and mutual reflections (Bloj, Kersten & Hurlbert, 1999). This would explain why colour constancy was quite poor in our experiments, although we used real scenes, which could be expected to lead to good colour constancy (Brainard, Brunt & Speigle, 1997). Subjects may have noticed that the objects were chromatically biased, and therefore avoided relying on the Grey World Hypothesis. Thus subjects may rely on the Grey World Hypothesis to achieve colour constancy under some conditions, but recognize that they should not do so in others, such as the present ones. In any case, the present study shows that we do not automatically rely on the Grey World Hypothesis to isolate surface reflectance from influences of the illumination.

We found differences in reliability between subjects' matches with the Pantone Specifier and with a CRT. The Pantone Specifier provided the most reliable matches. There were also large systematic differences (see figure 4). This suggests that there is some fundamental difference between the matching tasks (Schneider & von Campenhausen, 1998, but see Speigle, 1997). We were able to exclude some low-level explanations for the differences in results found between the Pantone Specifier and the CRT matching condition. We conclude that there must be some more subtle or fundamental difference between the matching conditions.

6
Colour matching between reflected and emitted light; Are there fundamental differences?

Submitted as:
Granzier JJM, Brenner E, & Smeets JBJ.
Colour matching between reflected and emitted light; Are there fundamental differences?

Abstract

Subjects match patches differently when instructed to make them look identical in hue and saturation than when instructed to make them look as if they were surfaces painted in the same colour. This suggests that subjects can distinguish between matching colours in terms of surface reflectance and in terms of reflected light. Are these really two distinct perceptual judgments, or is the former an interpretation of the latter based on the context, as when judging depth in pictures? Here we examine whether 'knowing' whether one is matching reflected or emitted light matters. We compared matches between colours that were both presented on a computer monitor or both as pieces of paper, with matching the colour of a piece of paper with a colour presented on a computer monitor and vice versa. If there is a fundamental difference between judging reflected and emitted light, the latter matches should be poorer. Instead, performance was specifically poor when matching an image on a computer monitor to the colour of a piece of paper, both in terms of systematic errors and in terms of the variability between subjects. We propose that matching the light reaching the eye and matching surface reflectance are indeed fundamentally different, but that subjects cannot freely choose which to match.

Introduction

Computer monitors are often used to study colour vision (e.g., Troost & de Weert, 1991; Cornelissen & Brenner, 1995; Yang & Shevell, 2003; Lucassen & Walraven, 1996; Granzier, Brenner, Cornelissen, & Smeets, 2005). Using a computer monitor has the advantage of flexibility in the design of stimulus characteristics and allows a good deal of automatized data collecting. However, using a computer monitor has the disadvantage of requiring repeated colorimetric calibration (Brainard, 1989; Lucassen & Walraven, 1990), restricting the luminance and colour gamut, restricting the viewing angle (Kraft & Brainard, 1999; Hurlbert, 1999; Murray et al., 2006), and in many cases omitting possible relevant factors such as shadows, mutual reflections (Drew & Funt, 1990; Bloj et al., 1999) and specular highlights (Lee, 1986).

Presenting colours on a computer monitor may even have a more fundamental disadvantage, because there may be a fundamental difference between looking at simulated surfaces on a computer monitor and looking at real surfaces (Schirillo, Reeves & Arend, 1990; Agostini & Bruno, 1996). Since the coloured patches on a computer monitor are actually light sources, some authors point out that it is even misleading to speak of errors in judging surface colours in simulated displays, because the stimulus itself is ambiguous (Hurlbert, 1999; Kraft & Brainard, 1999). Such ambiguity may underlie the fact that some subjects perform differently when asked to judge surface reflectance than when asked to judge the reflected light (Arend & Reeves, 1986; Arend et al., 1991; Troost & de Weert, 1991; Cornelissen & Brenner, 1995). When judging surface reflectance in a scene that does not really consist of surfaces that reflect light, subjects may weigh contextual information differently than they do when looking at real scenes, much as judging the distance to an object within a picture involves interpreting the cues that are present in the depicted scene (such as linear perspective and texture gradients), while ignoring ones that help estimate the distance to the picture itself (such as binocular disparity).

If the way we judge colour is fundamentally different when evaluating the extent to which real surfaces reflect different wavelengths of light and when estimating the composition of light emitted by a source such as a computer monitor, colour matches should be worse (larger systematic errors that may differ between subjects) when the test and reference are presented in different ways (matching the colour on a computer monitor to that of a real piece of paper) than when they are both presented in the same way (both as real surfaces or both on a computer monitor). We recently found significantly better colour matches when a real surface had to be matched in colour and luminance by selecting the appropriate sample from a colour selector (real coloured papers), than when it had to be matched with a surface on a computer monitor (Granzier, Smeets & Brenner, 2006). These differences were present even though we took care to match the tasks in various ways. Here we test all four possible combinations of the different ways in which the reference and test colours can be presented.

In our previous study (Granzier, Smeets & Brenner, 2006), the illumination was varied to evaluate subjects' colour constancy. Here we had a constant illumination. When matching real papers with real papers, the illumination of both papers was very similar, so we can consider a match of the reflected light to be a correct match for both surface reflectance and the light reaching the eyes. We therefore expect very good colour matches. When the colour of a piece of paper is matched with that of an image on a screen, matching anything but the light reaching the eyes can give rise to systematic errors, which may differ between subjects as a result of differences in the extent to which the chromaticity of the light reaching the eyes is attributed to reflectance. Similarly, systematic errors may be introduced when the reference is displayed on a computer monitor, because the light that reaches the subjects' eyes from the computer screen is a combination of reflected light from the lamp illuminating the scene and light emitted by the computer monitor, so subjects would have to evaluate the extent to which the colour of the light reaching their eyes is reflected. Thus, if subjects always match the light reaching their eyes, we expect no difference between the conditions. If they always match estimated reflectance we expect poorer performance when not matching paper with paper. If what subjects match depends on whether they are presented with reflected or emitted light, we expect poorer matches when matching papers with a computer monitor and vice versa.

Methods

The experimental room

The experimental room was split into two parts. Far from the subjects was a region for presenting the 'reference colours' (i.e. the colours that had to be matched). The reference colours were either presented as real coloured papers ('reference paper') or as colours on a computer monitor ('reference monitor'). Nearer to the subjects was a region in which subjects matched the colours (see figure 1). The walls of the room were black.

When the reference was presented on a computer monitor, the whole screen of the computer monitor was filled with the reference colour. The reference monitor was surrounded by various common household objects (e.g. a waste paper basked, a towel, a cup) of various colours, and was about 5 m from the subject. When the reference was a piece of paper, it was placed about 3.5 m from the subject. The reference paper was placed between the subject and the monitor. The reference paper was held in position by a clip of the kind used to hold photographs. It was placed manually by the experimenter. It was not placed extremely precisely, and the subject's head was not fixed, but subjects were instructed to maintain a head position for which the reference paper more or less occluded the screen of the computer monitor. The small difference in alignment could have some influence on local contrast, perhaps slightly increasing the variability between trials when matching the reference paper. Part of the white borders of the monitor was visible so that the directly surrounding colours were about the same when the reference colour was presented on the monitor as when it was a piece of paper. The reference paper was placed in such a way that it was illuminated by the lamp illuminating the scene (see figure 1). The dimensions of the reference paper did not correspond precisely with those of the reference colour presented on the computer monitor, and the paper was clearly closer, so that it was perfectly clear that the paper was not simulated. Thus, subjects were always clearly aware of whether the reference colour was being presented as a self-luminous patch (computer monitor) or as a reflecting surface (paper). During presentations in which subjects had to match reference papers the reference monitor was off.

The reference papers

There were only 6 reference colours, but subjects were

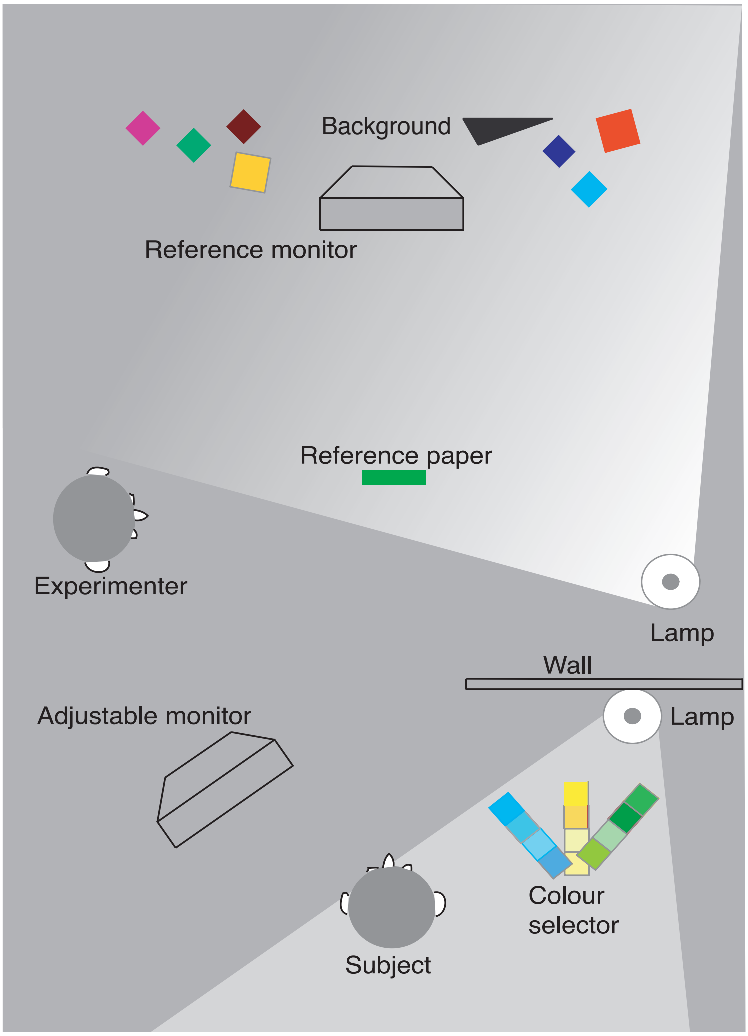


Figure 1: Schematic overview of the experimental room. Subjects sat 5 meters from the reference when it was presented on the computer monitor and 3.5 meters from the reference when it was a piece of paper. The reference monitor was embedded in a background of real common objects. The whole scene was illuminated by a lamp. Subjects either matched the reference colour with the colour selector or with an adjustable patch on a computer monitor.

not aware of this even after running the experiment. The coloured papers were A4 format (29.6 x 21.1 cm). Under daylight illumination, they looked green, pink, purple, light blue, dark blue and white. Under the lamp that we used to illuminate the scene, the reference papers reflected light with 1931 CIExyY coordinates (0.42, 0.48, 5.77 cd/m^2), (0.51, 0.36, 7.25 cd/m^2), (0.45, 0.40, 11.6 cd/m^2), (0.43, 0.41, 11.1 cd/m^2), (0.34, 0.38, 2 cd/m^2) and (0.45, 0.41, 14.9 cd/m^2).

The reference monitor

The references monitor had an effective image size of 32 cm x 23 cm (1280 x 1024 pixels; 85 Hz; 8 bits per gun). The lamp that illuminated the background (and the papers when the reference papers were used) also illuminated the monitor, so the calibration (using a Minolta CS-100A chroma meter) was conducted with this lamp on. The light that reached the subject' eyes was therefore identical to that reflected by the paper, but it was a combination of emitted and reflected light. We used six CIExyY values for which the light that reached our subjects' eyes was as close as possible to the light from the reference papers illuminated by the lamp (see values above). The outer edges of the computer monitor (white plastic) were 4.5 cm wide.

The colour selector

For colour matching using real papers, we used a colour selector (Pantone, New Jersey, 1984). Subjects had to select the sample that best matched the colour and luminance of the reference. Subjects were free to leaf through the "pages" until they found a suitable sample. Once they had found a right match, subjects read out the number of the matched colour and the experimenter wrote down the number and the next reference colour was presented. When matching with the colour selector, the adjustable computer monitor (see below) was off.

The Adjustable computer monitor

A calibrated computer monitor (40 cm x 30 cm; 1280 x 1024 pixels; 90 Hz; 8 bits per gun) was 1 m from the subject. Subjects had to match the colour and luminance of an adjustable patch to the colour and luminance of the reference. There were only two colours on the screen: the colour set by the subject (within a 5 deg diameter adjustable patch at the centre of the screen) and a uniform background (10 cd/m^2) with the same coordinates (0.47, 0.42) as the light from the "white" background of the colour selector when illuminated by the lamp that we used (see below). The patch's chromaticity was manipulated (within the part of the CIE colour space that we could render on the monitor) by moving the computer mouse. Subjects could manipulate the luminance by pressing the arrow keys on the computer keyboard. They indicated that they were content with the match by pressing the mouse button. The initial hue of the adjustable patch was determined at random for each match from within the range that could be rendered. The luminance of the adjustable patch was 10 cd/m^2 for the first match, but it remained at whatever value the subject set for the next trial.

Lamps

We used two lamps in our set-up (see figure 1). One lamp illuminated the scene (including the reference monitor and reference paper, when present). This lamp was always on. Another lamp was only used when subjects matched the reference colour with the colour selector. The two lamps were similar in both intensity and colour. Both lamps had 1931 CIExy coordinates of (0.47; 0.41) as measured directly with a Minolta CS-100A chroma meter. The lamp illuminating the scene was positioned between the subject and the scene, slightly to the right of the observer (see figure 1), so that it would illuminate the front surface of the reference paper as well as the background with the reference monitor. The lamp illuminating the colour selector was positioned in such a way that it only illuminated the colour selector and the black surface on which it rested, but obviously the subjects' hands were visible when manipulating the Colour selector.

Subjects and Procedure

Four subjects (including the second author), with normal colour vision as tested with Ishihara colour plates (Ishihara, 1969), participated in the experiment. Except for the author, the subjects were naïve as to the purpose of the experiment. After adapting to the light in the room for 5 minutes while receiving instructions, each subject made 30 matches (6 reference colours, each presented 5 times). This was done in a separate session for each of the 4 comparisons. Within each session, the reference colours were presented in an arbitrary order. Subjects could take as much time to find a suitable match as they liked. The experimenter changed the reference manually after each match had been made. For the reference paper, this was done by replacing the paper held by the clip (see above). For the reference monitor, the experimenter typed a number corresponding to the desired reference colour and the uniform colour on the screen changed accordingly. When the reference was presented on the computer monitor, there was obviously no reference paper attached to the clip. The order of conditions in which subjects were tested was counterbalanced (Latin square).

Analysis

We first converted the chosen samples of the colour selector into 1931 CIExyY coordinates by measuring the light that they reflect when illuminated by the lamp illuminating the colour selector during the experiment. We then determined the mean values of each subject's matches for each of the four conditions (paper-paper, monitor-monitor, paper-monitor and monitor-paper, where the first term refers to the reference and the second to the presentation used to match the reference) and six reference colours. This means that for each condition we had 24 mean matches (4 subjects x 6 reference colours). Beside plotting these matches we also determined a single value (for each condition) for the average systematic error (the deviation of the four subjects' mean colour matches from a perfect match of the light from the two surfaces, as a distance in CIExy colour space) and for the variability between subjects (the median distance in CIExy colour space between the 4 subjects' colour matches for

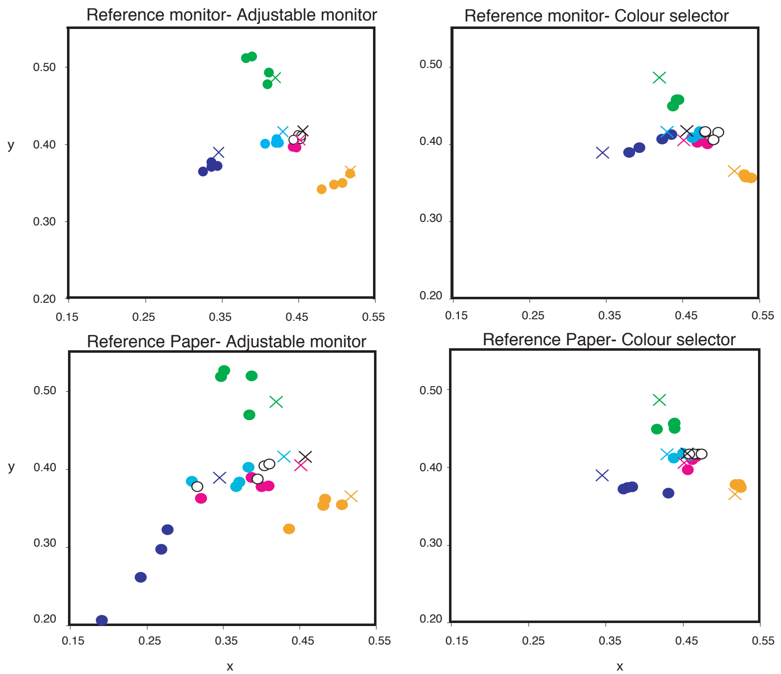


Figure 2:
1931 CIE coordinates of each of the four subjects' average colour matches (circles) and of the light reaching the subjects' eyes from the reference (crosses) in each of the four conditions (different panels). The different colours of the symbols represent different reference colours.

the same reference, averaged across references).

Results

Figure 2 shows the average colour matches (circles) for each subject for each of the 4 conditions (separate panels). Also shown are perfect matches of the light reaching the eyes (crosses). The different colours in the figure represent the different reference colours. From this figure we can directly see that there are exceptionally large biases in subjects' colour matches for the condition in which reference papers are matched on an adjustable computer monitor.

A repeated measures ANOVA on the average systematic error (see figure 3) per reference colour in each condition, showed that there was a systematic difference between the four conditions ($F3=16.3$, $p<.0001$). Post-hoc (Bonferoni corrected)

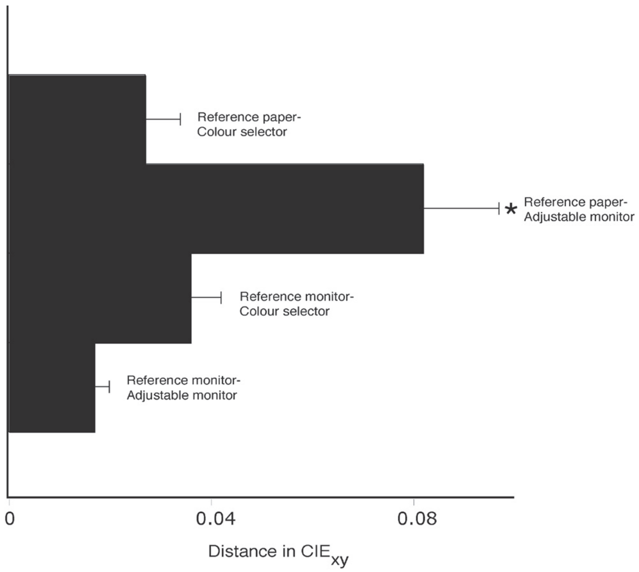


Figure 3: Systematic errors in the average of the four subjects' colour matches as distances in CIExy (averaged across the 6 references with standard errors across references).

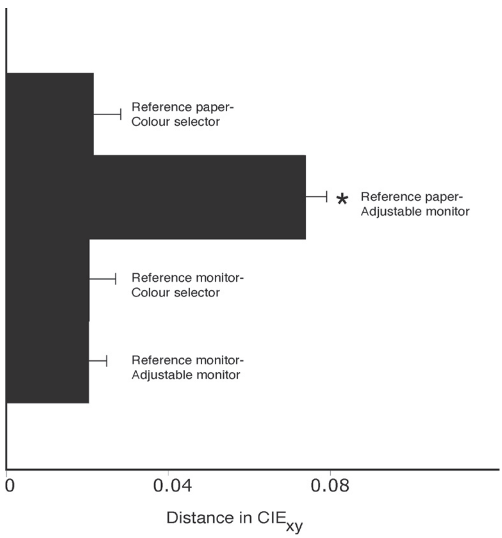


Figure 4: Variability between the four subjects' colour matches (the median distance in CIE colour space between the four subjects' colour matches for the same reference, averaged across references with standard errors).

tests showed that the subjects' performance was worse when reference papers had to be matched with an adjustable computer monitor than in the other three conditions. The other three conditions were not significantly different from each other.

Figure 4 shows the average variability in colour matches between subjects for each of the four conditions. A repeated measures analysis of the median difference between the subjects' settings (i.e. the variability between subjects) for each reference colour also revealed a significant difference between the conditions (F3=22.6, $p<.0001$). Post-hoc tests showed that there was significantly more variability between subjects in the condition in which they matched reference papers with an adjustable computer monitor than in the other three conditions. Again, there were no significant differences between the other three conditions.

Discussion

We are aware that there were some differences between the images on the retina when reference colours were presented on a computer monitor and when they were presented as real papers. Such differences could influence subjects' colour matches. It was impossible to control all such details. For example, when subjects matched reference colours with the colour selector, their hands and other colour samples were in sight. The background was also not completely identical when reference colours were presented on a monitor as when they were presented as real papers, because the paper was at a different distance, filled a slightly larger part of the visual field, and was slightly less uniform in luminance because it was often slightly curved. However, such differences can only be expected to marginally influence the matches, and are essential if the subject is always to be aware of whether he or she is dealing with emitted or reflected light. In the present study we were interested in larger (more fundamental) differences between the conditions.

Subjects made different systematic errors in the different matching conditions (compare the four panels of figure 2). In the introduction, we explained that if knowing whether one is judging emitted or reflected light has an influence on how we judge colours, we should find the best colour matches when reference colours were presented as real papers and were matched with other real papers. We did not find this. Neither is specifically finding poor performance when colours presented on paper were matched with colours presented on an adjustable monitor (both larger errors and more variability between subjects' matches; figures 3 and 4) consistent with any of the other patterns that we proposed in the introduction.

If the difference between the conditions had been caused by the different distance of the reference surface or some other aspect of the reference, we would not only have found poorer performance when matching the reference paper on the adjustable monitor, but also when matching it by selecting a matching sample from the selector. Similarly, if finding an appropriate colour on the monitor were less reproducible than finding the correct piece of paper, we would have also found poor performance when matching the reference monitor in this manner. The fact that the distinction neither only depended on the kind of reference nor only on the way it was matched suggests that the difference cannot be due to some uncontrolled aspect of the presentation. There must therefore be something fundamentally different between the different comparisons. The obvious suggestion is that a difference between judging reflected and emitted light somehow accounts for this pattern of results.

We propose the following explanation for the unexpected pattern of results. The reference colours presented on the monitor (that is embedded within the scene and is illuminated by the lamp that illuminates the scene) can be matched in terms of either surface reflection or emitted light. When matched in terms of reflection it is not considered to emit light and when matched in terms of emitted light it is not considered to reflect light, so no errors are introduced by trying to dissociate reflected from emitted light. The reference paper and the papers of the selector can only be considered in terms of surface reflectance. The variable patch on the adjustable monitor can only be considered in terms of the light reaching the eye, because the illumination cannot be judged in any reasonable manner, so subjects would have to guess what the illumination could be, and the ever-changing patch cannot be a painted surface. Thus, subjects can match reference colours presented on a monitor with a patch on another monitor in terms of the light reaching the eye. They can match reference colours presented on a monitor with the colour selector in terms of surface reflectance. They can obviously also match real papers with other real papers in terms of surface reflectance. The problem arises when matching a real surface (which is difficult to interpret in terms of the light reaching the eye) with a variable patch on a monitor (which is impossible to interpret in terms of surface reflectance). If this proposal is correct then there is a fundamental difference between judging emitted and reflected light, but subjects will seldom be free to choose which judgment to make.

7

Luminance – Color Correlation is not used to estimate the color of the illumination

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Luminance-color correlation is not used to estimate the color of the illumination.
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Abstract

Humans can identify the colors of objects fairly consistently, despite considerable variations in the spectral composition of the illumination. It has been suggested that the correlation between luminance and color within a scene helps to disentangle the influences of illumination and reflectance, because the surfaces that reflect the light of the illuminant well will normally be bright.

Since the reliability of the luminance-color correlation as an indicator of the chromaticity of the illuminant depends on the number of surfaces that are considered, we expected the correlation to be determined across large parts of the scene. To examine whether this is so, we compared different scenes with matched luminance and chromaticity, but in which the correlation between luminance and chromaticity was manipulated locally.

Our results confirm that there is a bias in perceived color away from the chromaticity of bright surfaces. However, the results show that only the correlation within about 1° of the target is relevant. Thus, it is unlikely that the visual system uses the correlation between luminance and color to explicitly determine the chromaticity of the illuminant. Instead, this correlation is presumably implicitly considered in the way that the color contrast at borders is determined.

Introduction

Our visual system somehow manages to recover surfaces' spectral reflectances despite the fact that the spectral distribution of the light reaching our eyes is determined just as much by the spectral distribution of the illumination as by the surfaces' chromatic properties. Without additional knowledge or assumptions, either about the illuminant or about the surfaces' reflectance, it is impossible to separate the two.

Assumptions about the way in which the visual system disentangles illumination from reflection include the possibility that the average reflectance of the whole scene is grey (Buchsbaum, 1980; but see Brown, 2003) or that the brightest surface is white (Land & McCann, 1971; but see Linnell & Foster, 2002). Obviously, these assumptions are not always correct, and simple experiments show that they cannot explain human color constancy (also see Kraft & Brainard, 1999).

Recently, Golz & MacLeod (2002) proposed a new, more robust variant of the 'brightest surface is white' hypothesis. They suggested that the human visual system does not only rely on the brightest surface in the visual scene (assuming that it is white so that the spectral distribution of the light that it reflects is that of the illumination), but rather relies on the correlation between luminance and color across the whole scene to estimate the color of the illumination. If there are many surfaces in a scene, with a large variety of reflectance properties, then it is reasonable to assume that on average the surfaces that reflect well in the color of the illuminant will be brighter. For instance, if the illuminant is reddish, then the surfaces that reflect red light particularly well (i.e. red surfaces) are likely to be brighter than the surfaces that reflect green light particularly well (i.e. green surfaces), leading to a high correlation between luminance and redness within the scene. Thus, this strategy could help disentangle reflectance properties from biases in the illumination, without placing too much emphasis on a single surface.

Golz and MacLeod (2002) presented subjects with scenes in which there were different amounts of correlation between color and luminance, but that had the same average chromaticity and luminance. They found that a test field had to be redder for it to appear perceptually achromatic when the correlation between luminance and redness was high. This is consistent with subjects interpreting the positive correlation between luminance and redness in terms of there being a reddish illumination. Thus the perceived color was biased away from the color of the brighter patches in the scene, even if the average chromaticity and luminance was held constant.

Golz & MacLeod (2002) implicitly assumed that the luminance–color correlation is determined for the whole scene, or at least their whole display, because that is what one would expect if this scene statistic is used to determine the chromaticity of the illuminant. In the present study we examined whether this is really the case. We did so by asking subjects to set the color of a disk in a simple computer generated scene. The scene was divided into fields. Each field was built up of squares with two colors: either bright red and dark green, or bright green and dark red (see figure 1), equivalent to Golz and MacLeod's fields with a luminance-color correlation of 1. We varied the size of the field surrounding the target, to examine whether this region was of particular importance. When this 'near field' did not cover the whole background, it was always surrounded by a field with an opposite correlation between luminance and color.

Like Golz & MacLeod (2002), we compared conditions in which we ensured that the pairs of field colors give the same space-averaged excitation of each type of cone (we refer to this as the 'matched sum' balancing method). However, this meant that the darker field colors were more saturated, because lowering the excitation of one type of cone influences the ratio between the stimulation of different types of cones more strongly than increasing the excitation of the same type of cone by the same amount. Since chromatic induction may take place after cone opponency (Brenner & Cornelissen, 2002), and the correlation between luminance and saturation may also be considered (Gilchrist, 2004), such saturation differences could influence the results. If saturation is important, it is not quite appropriate to match the summed cone excitation. We therefore also included conditions in which we matched the cone ratios between the high luminance colors and the low luminance colors (we refer to this as the 'matched ratio' balancing method). Obviously, in this case the average L-cone and M-cone excitation was no longer matched.

Experiment 1

Methods

Subjects

Ten subjects took part in the experiment. They had normal color vision as tested with Ishihara color plates (Ishihara, 1969). One subject was the first author. The other subjects were naïve as to the purpose of the experiment. This research is part of an ongoing research program that has been approved by the local ethics committee.

Apparatus

The stimuli were presented on a high-resolution Sony GDM –F520 Trinitron monitor (39.2 cm X 29.3 cm; 1024 X 768 pixels; 120 Hz; 8 bits per gun) in an otherwise dark room. Subjects sat 100 cm from the screen with their chins and foreheads supported. The influence of various backgrounds on the color appearance of a central disk was determined using the hue-cancellation procedure (Jameson & Hurvich, 1955): We determined the physical stimulus that appears to be a neutral grey within different scenes. The extent to which light from each surface stimulated each of the three cone types was determined on the basis of average relative spectral sensitivity functions of human cones (Pokorny & Smith, 1986, chapter 8).

The adjustable disk

The stimulus consisted of a two deg radius adjustable disk at the centre of a 16 deg x 16 deg square background (figure 1). The luminance of the adjustable disk was 21 cd/m^2.

The background

The background consisted of an array of 38 by 38 squares. Each square subtended approximately 42 min of arc. It was either red or green (determined at random for each presentation) and either bright or dark. The background could be divided into two fields, a near field and a far field, where 'near' and 'far' refer to the distance from the adjustable disk. Within a field, either all green squares were bright and all red squares were dark, or vice versa. There were four different near field configurations (figure 1). The near field could either fill the complete background (the 'all' configuration), or it could fill a ring of 4°, 2°

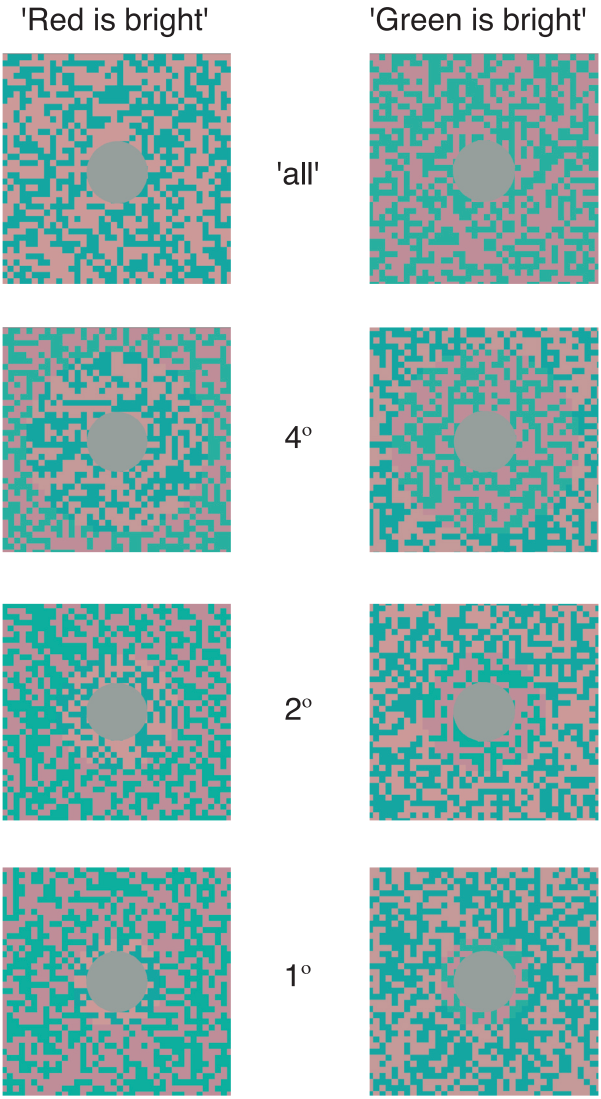
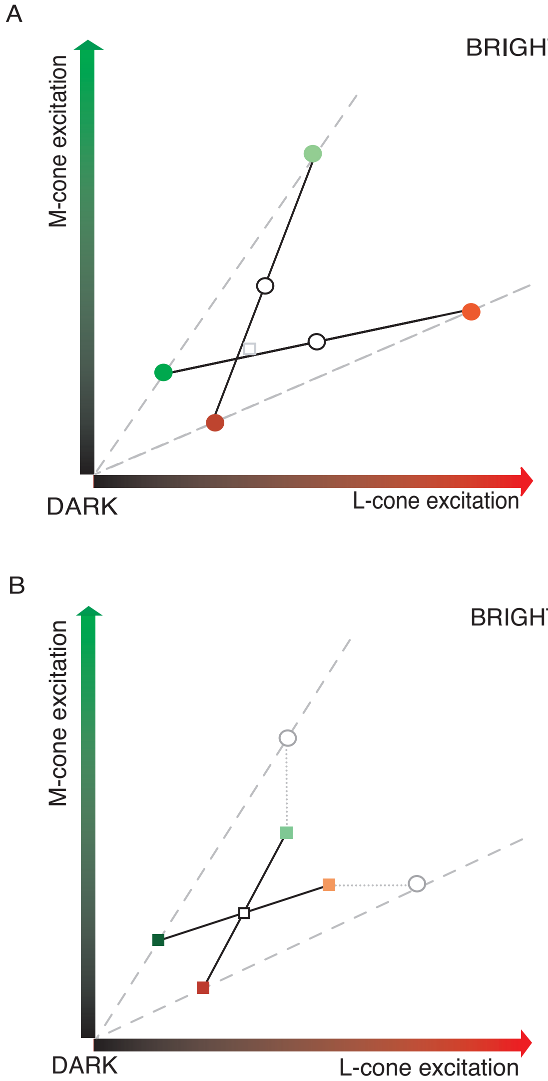


Figure 1: The four field configurations and two luminance-color correlations in experiment 1. The adjustable disk was at the center of a background of red and green squares. The square background could be divided into two fields: a near field consisting of a rim of squares surrounding the adjustable disk, and a far field filling the rest of the background. The rim could fill the whole background or it could extend for 4°, 2° or 1° from the disk. Within each field either the red squares were brighter than the green, or vice versa. The fields are named by the bright color of the near field.

or 1º width surrounding the adjustable disk. For the latter three configurations, the higher luminance was correlated with the other color in the far field than in the near field. This meant that if the red squares were brighter in the near field, the green squares were brighter in the far field, and vice versa. We will name the luminance-color correlation by the color of the bright squa-



A: The matched ratio balancing method. The colored circles represent the colors that could be present. The mean luminance and chromaticity (open circles) are not the same for the two possible combinations of color and luminance. B: The matched sum balancing method. The colored squares represent the colors that could be present. The open square represents the mean luminance and chromaticity, which was the same for both combinations of color and luminance (20 cd/m^2; x= 0.29, y= 0.30). The open circles and dotted lines show how the bright colors were changed relative to their values for the matched ratio balancing method in order to achieve this (for further details see methods of experiment 1).

Figure 2: Schematic (highly exaggerated) representation of the two balancing methods. Dashed lines represent constant cone excitation ratios. Solid lines connect the two colors of each field: bright red and dark green or bright green and dark red.

res in the near field, so a 'red is bright' luminance–color correlation means that the red squares in the field near the adjustable disk are bright. All the background squares provided the same S-cone excitation, irrespective of their color and luminance.

The two balancing methods

There were two different color-balancing methods, the 'matched ratio' method (figure 2a) and the 'matched sum' method (figure 2b). For the matched ratio method, there were the same two ratios between the stimulation of L- and M- cones within each field. The two possible ratios between L and M cone excitations are represented schematically by the dashed lines in figure 2a.

For each of these ratios, the bright squares had a 20% higher luminance than the dark ones. Each field consisted of squares with the higher luminance for one of the ratios (colors) and squares with the low luminance for the other ratio (see pairs of points connected by lines in figure 2). The ratio of the L and M cone stimulation was 20% larger for the red squares (shallower dashed line) than for the green squares (steeper dashed line). The space-averaged luminance and chromaticity of the two fields was not the same (open circles).

For the matched sum method (figure 2b), the sum of the L- and M- cone stimulations within each field was the same (open square). To achieve this we reduced the stimulation of the L-cone in the bright red squares and of the M-cone in the bright green squares, so that the overall average luminance and chromaticity (20 cd/m^2; x= 0.29; y= 0.30, open square in both panels of figure 2) was the same for the 'red is bright' and 'green is bright' fields. This decreased the saturation of the bright fields. The mean luminance of the background for the matched ratio balancing method was almost 1% higher than for the matched sum balancing method.

Procedure

Subjects were asked to set the adjustable disk so that it would appear grey. They could vary its color within a two dimensional isoluminant color space by moving the computer mouse. Subjects indicated that they were content with the set value by pressing a button. Once they did so, a new stimulus appeared. The initial color of the adjustable disk was determined at random from within the range that they could set. Subjects were not instructed to fixate the adjustable disk, although we expected them to direct their gaze at it most of the time anyway (Cornelissen & Brenner, 1995). After dark adapting for 10 minutes, each subject made 200 settings: each combination of the 4 field configurations, 2 balancing methods and 2 luminance-color correlations ('red is bright' or 'green is bright'), each presented 10 times except for the 'all' configurations that were presented 20 times. We doubled the number of trials for the 'all' configuration because this was our baseline. All the trials were presented in random order. A new field was generated for each trial.

Analysis

We first determined the mean L-cone value and the mean S-cone value of each subject's settings for each of the 16 experimental conditions. Note that there was no need to also examine the M-cones, because the settings were made at a fixed luminance. To obtain a measure of how the luminance-color correlation in the field influenced what was perceived as a grey disk, we calculated the difference between the settings when 'red is bright' and when 'green is bright' in the near background (for each cone). We will refer to such differences as 'difference scores'. We calculated difference scores for each balancing method and field configuration. This was done separately for each subject, and separately for the L-cone values and the S-cone values.
For the 'all' configuration, we expected the L-cone excitations that subjects set when 'green is bright', indicating a greener

illumination, to be lower than those set when 'red is bright', indicating a redder illumination. Thus, we expected a positive difference score. For the configurations with near fields that do not fill the whole background, we expect the difference score to be smaller. As the near field becomes smaller, we expect the difference score to become negative. When the near field decreases to a width of zero, the difference score will reach the same value as in the 'all' field configuration, but with an opposite sign, because it is precisely the same stimulus (but with an opposite assignment of the names to the luminance-color correlations). The 'all' field configuration is equivalent to the configuration that Golz & MacLeod used in their experiments (Golz & MacLeod, 2002). As already mentioned, we used this configuration as a baseline. T-tests were used to determine whether the subjects' difference scores in the 'all' configuration were consistently different from zero. Repeated measures analyses of variance were used to evaluate the influence of the field configuration (1°, 2°, 4°, 'all') on the difference scores for each balancing method.

Results

Figure 3 shows the mean L-cone difference scores for the four near-field configurations and the two color- balancing methods. The mean L-cone difference scores for the 'all' baseline configuration show a clear trend in the predicted direction (a positive difference score), but these difference scores were only significant for the matched ratio balancing method ($t(9)= 5.53$, $p< .001$). For the matched ratio balancing method, there was also a significant influence of field size ($F(1, 3) = 6.89$, $p= .001$) on the mean L-cone difference scores, but the difference scores did not decrease systematically with decreases in near field size as we had expected. For the matched sum balancing method, the mean L-cone difference score for the 'all' configuration was positive, but it was not reliably different from zero ($t(9)=1.53$, $p= .16$). No effect of field configuration was found for the L-cone excitation ($F(1, 3)= .43$, $p= .733$). No significant baseline effects and no effects of near-field configuration were found for the S-cone excitation. We had not expected such effects, because we only varied the L- cone and M-cone stimulation in the background.

Discussion

For the uniformly correlated field ('all' configuration), the difference scores for the L-cones confirm that there is a shift in perceived color away from the chromaticity of the bright surfaces (positive difference scores). This shift in perceived color is

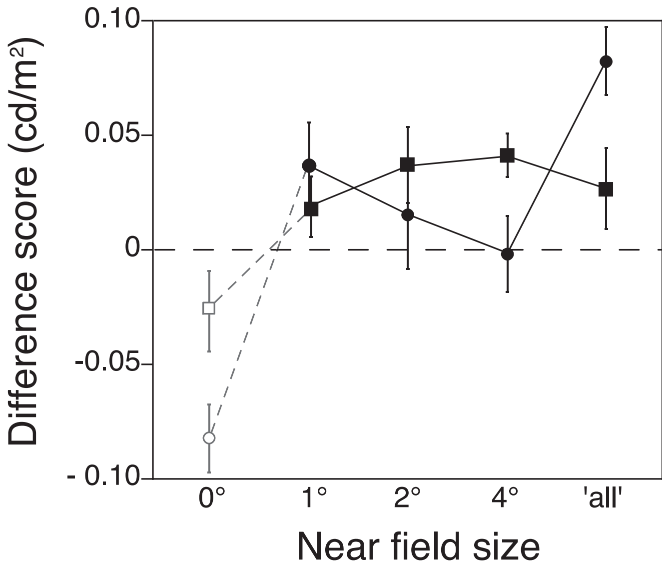


Figure 3: Results of experiment 1. Mean 'difference scores' for the L-cone as a function of near field size. Filled circles: matched ratio balancing method; Filled squares: matched sum balancing method. The data for the 'all' configuration have been reproduced as a 0º near-field configuration, with the sign inverted to reflect that the whole background is now considered to be a far field (open symbols). Error bars show the Standard Error between subjects.

in accordance with an assumed illumination that is biased in the direction of the color of the bright surfaces. However, this shift was only significant for the matched ratio balancing method. There was also a significant effect of the field configuration for the matched ratio balancing method, but this effect was not due to a systematic change in the difference scores with near field size, so it is difficult to interpret (see figure 3). Remember that for the matched ratio balancing method, the shift in perceived color might be explained by the difference in mean cone excitation between the two backgrounds.

The perceived color also appeared to shift in the direction of the color of the bright surfaces for the matched sum balancing method, but this shift was not significant for the 'all' configuration. Since there was no effect of field configuration for the matched sum balancing condition, we also averaged each subject's difference scores for the four field configurations to see whether the average difference scores differ significantly from zero. The average difference was indeed significantly different from zero when all field configurations were grouped together ($t(9) = 4.726$, $p = .001$).

If the correlation between chromaticity and luminance within the whole scene had been used to estimate the chromaticity of the illuminant, we would have expected the difference scores to be positive for the largest near-field configuration ('all') and to decrease to negative values as the near-field configuration decreases in size. The near and far fields would have covered the same surface for a near field width of 6.3°. Thus, if the luminance-color correlation had been determined for the whole scene, we would have expected negative values for all the near-field configurations except for the 'all' configuration. However, even for the 1° near field width we see a tendency for positive difference scores (see figure 3). This suggests that only the luminance-color correlation within the surfaces that are adjacent to the surface of interest may be relevant. However, the fact that the baseline difference score was only significantly different from zero for one of the balancing methods warns us to be a bit cautious with such a conclusion. We therefore decided to repeat the experiment with a more sensitive task and even smaller near-field widths.

Experiment2

The apparatus and procedures were identical to those of experiment 1. The main difference was that in the new experiment a matching task was used instead of a nulling task. The disadvantage of a matching task is that we need two targets with different fields, so that the overall luminance-color correlation cannot be as high. In fact, we always used symmetrical fields, so that the overall correlation was always zero. Thus if the impression that we got from experiment 1 was incorrect, we expect to find no effect at all. The advantage of using a matching task is that the reference color is specified explicitly, which we expected would reduce the variability in the settings. We used pairs of backgrounds, each of which was a slightly narrower version of those of experiment 1 (see figure 4). We used the same colors as in experiment 1. If red was bright in one near field, green was bright in the other near field.

If only the luminance-color correlation near the target is important for the perceived target color, as is suggested by the results of experiment 1, the influence of the correlation could be twice as large here, because the two targets (reference disk and adjustable disk) are each influenced, but in opposite directions. However, we realize that the influence does not need to be exactly twice as large, because there will be differences in viewing strategies between the two tasks, which may influence the color settings that people make (Cornelissen & Brenner, 1991, 1995). In a matching task, subjects move their eyes from the test to the adjustable disk, ensuring that a comparison can be made with the eyes in an almost identical state of adaptation. Thus changes in adaptation will not necessarily influence the settings. In a nulling task, subjects fixate on the adjustable disk. Since adaptation will not change the remembered reference (in our case grey), it is likely to influence the settings.

Methods

Subjects

Eleven subjects with normal color vision took part in the experiment. Eight of the subjects had also participated in the first experiment, including the first author. Other than the author, none of the subjects had any idea of the purpose of the experiment.

The reference disk & adjustable disk

A grey (CIE x=0.29, y= 0.30) reference disk with a luminance of 21 cd/m^2 was presented at the centre of the left background. The disk had the same radius as the disk used in experiment 1 (2 deg) and was centered on an 11 deg (width) x 16 deg (height) background (see figure 4). The observer's task was to match its appearance by manipulating the chromaticity of an equally sized adjustable disk of the same luminance that was presented on an equally sized background on the right. The color of the latter disk could be set within a two-dimensional isoluminant color space by moving a computer mouse.

The background

The fields on the left and right each consisted of an array of 25 by 38 squares. Each square subtended ap-proximately 42 min of arc. The same colors of the field squares were used as in experiment 1. Again, we had a 'matched sum' and a 'matched ratio' balancing method, with either the red or the green squares being brighter in the near field of the adjustable disk (on the right). We name the luminance-color correlations by the condition in this field (see figure 4). If the near field of the adjustable disk had bright red squares, then the near field of the reference disk (on the left) had bright green squares, and vice versa. For the far fields, we used the reversed luminance-color correlation that we used in the corresponding near fields. All the near field widths were halved, so that we now had near-field widths of 0.5º, 1º and 2º, beside the near field that filled the whole background on each side ('all' configuration). Thus, once again there were 16 different conditions (4 different field configurations, 2 balancing methods and 2 luminance-color correlations). Again, the 'all' configuration was treated as the baseline condition.

Procedure

After dark-adapting for 10 minutes, each subject made 200 settings: 16 conditions, each presented 10 times with an additional 10 trials in the four baseline conditions ('all' configuration). The 200 trials were presented in random order.

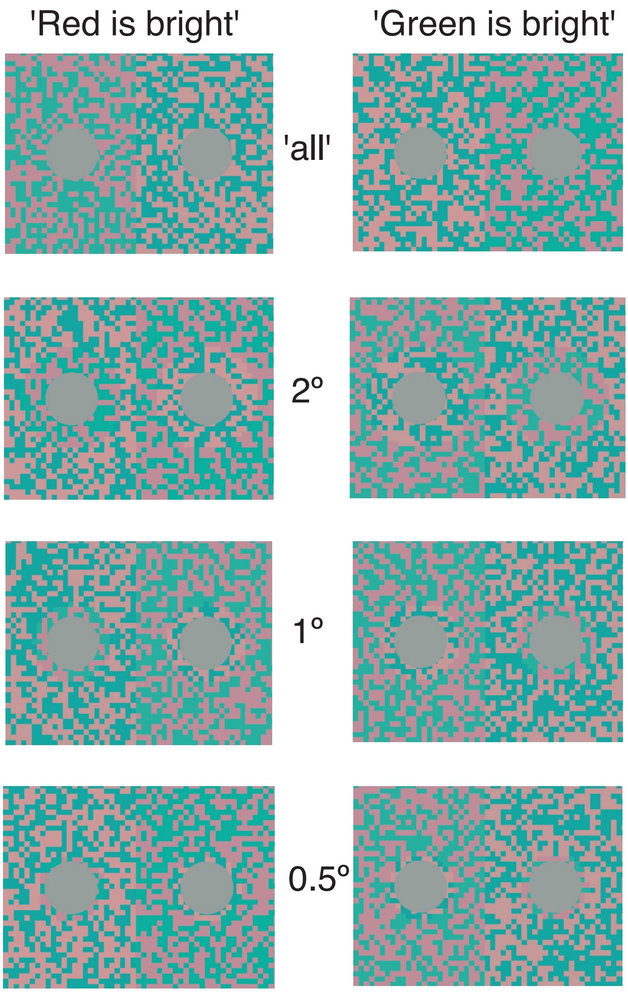


Figure 4: The four field configurations and two luminance color correlations in experiment 2. Subjects had to set the adjustable disk (on the right) to match the reference disk (on the left). Each half of the background was similar to that in experiment 1 (for details see figure 1). The fields are named by the bright color of the near field surrounding the adjustable disk (i.e. on the right).

Analysis

The data analysis was similar to that of experiment 1. The difference score was now defined as the difference between the adjustable disk's settings when the bright squares in the field near the adjustable disk were red ('red is bright') and when the bright squares near the adjustable disk were green ('green is bright').

Results

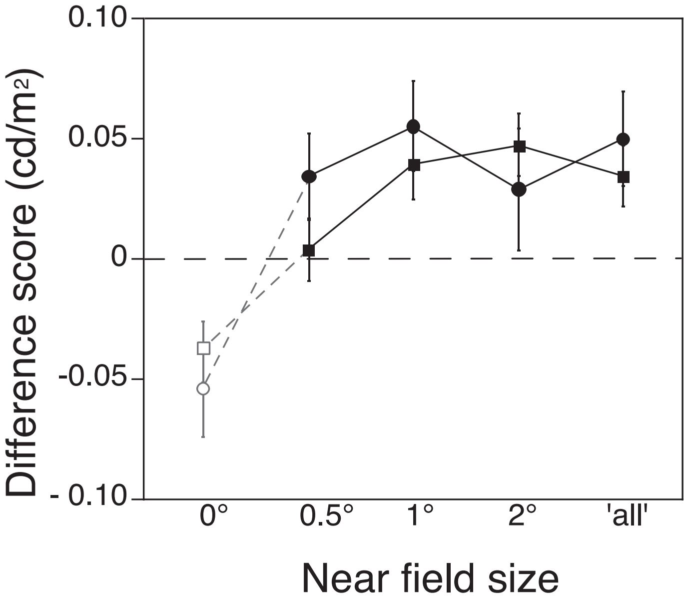


Figure 5: Results of experiment 2. Mean 'difference scores' for the L-cone as a function of near field size. Filled circles: matched ratio balancing method. Filled squares: matched sum balancing method. The data for the 'all' configuration have been reproduced as a 0° near-field configuration, with the sign inverted to reflect that the whole background is now considered to be a far field (open symbols). Error bars show the Standard Error between subjects.

Figure 5 shows the mean difference scores for the L- cones, as a function of the near-field configuration, for both balancing methods. One sample t-tests showed that the luminance-color correlation had an influence on the L-cone difference scores in the 'all' configurations, for both the matched sum ($t(9)= 2.87$, $p= .017$) and the matched ratio balancing method ($t(9)= 2.66$, $p= .024$). There were no significant main effects of field configuration for either the matched sum balancing method ($F(1, 3) = 1.99$, $p = .135$) or the matched ratio balancing method ($F(1, 3) = .46$, $p = .714$). Again, there were no significant effects for the S-cone difference scores.

Discussion

Experiment 2 confirms that the influence of the luminance-color correlation is a local effect. The strongest evidence for this is the fact that the effect is seen when two backgrounds with opposite luminance-color correlations are present in the scene, as was the case in all our displays in experiment 2. The fact that the difference score is almost the same for a 0.5º near-field configuration as for the largest configuration tested ('all'), suggests that the effect is limited to the border of the adjustable disk.

Conclusions

We found that the luminance-color correlation had an influence on the L-cone difference scores in the 'all' configurations. This finding is consistent with those of Golz & MacLeod (2002) who used equivalent experimental conditions. However, our results suggest that Golz & MacLeod (2002) were incorrect in their implicit assumptions that the visual system uses the correlation between luminance and color in the whole scene to derive the chromaticity of the illuminant. For the luminance-color correlation to provide reliable data for estimating the chromaticity of the illuminant (and thereby to separate surface properties from those of the illumination), it is crucial that not just a small part of the visual field is considered, because otherwise the colors of objects which happen to be within the relevant part (e.g. next to the object of interest) will dominate the perceived color (Brenner & Cornelissen, 1991).

We found that extending the color-luminance correlation beyond 1 degree of the test disk had little effect on color appearance. This spatial property is consistent with the spatial properties of chromatic induction (Walraven, 1973; Tiplitz-Blackwell & Buchsbaum, 1988; Brenner & Cornelissen, 1991). This raises the possibility that the present findings and those of Golz & MacLeod (2002) are the result of an interaction between color and luminance when the border contrast is determined. Asymmetries between the chromatic influences of brighter and darker background surfaces have been found before (e.g., Delahunt & Brainard, 2000; Bauml, 2001; Delahunt & Brainard, 2004a). In our case, we always have both brighter and darker squares next to the target. However, if the squares that have a higher luminance have a stronger influence on the perceived color, and the effects of all the surrounding squares are additive (Brenner et al., 1989), the summed effect will depend on which color was brighter. Such an asymmetry could explain our data. Moreover, it provides a way to use the ideas underlying Goltz and MacLeod's proposal for a modest contribution to color constancy without assuming that the illumination is uniform (which it seldom is in daily life).

The overall pattern of the difference scores for the two color-balancing methods was the same. This is not very surprising considering that the difference was extremely small, but it ensures us that the influence that we found is not just a consequence of having equated the fields at the wrong stage of processing. At least, our findings hold whether one equates the fields at the cone (matched sum balancing method) or at the color-opponent (matched ratio balancing method) stages of processing.

In conclusion, while we agree with Golz and MacLeod (2002) that there is a bias in chromatic induction away from the color of bright surfaces, we show that this bias is not used, as they implicitly suggest, to estimate the chromaticity of the illuminant from the correlation between luminance and chromaticity within the whole scene.

8
Epilogue

The status quo of colour constancy research

Our current understanding of colour constancy is patchy at best. Often results of experiments using different methodologies are compared in colour constancy research, without explicit acknowledgement that these experiments and their underlying processes may be quite different. The amount of colour constancy varies considerably from study to study which in part can be attributed to differences in viewing conditions, task procedures, stimulus characteristics and display techniques, as well as inter-observer variability. We still do not know whether we are measuring the same colour perception processes in the different tasks used. In chapter 5 of this thesis, we explored the effects of different matching tasks on colour constancy by keeping other variables as constant as possible. We found that colour constancy is dependent on the task used.

We also do not know what the different strategies or assumptions are that subjects use when performing in a colour constancy experiment. Observers may differ in their knowledge of illuminants and of how illuminant cues should be combined in a colour constancy experiment leading to large inter-subjects variability (e.g., Kraft, Maloney & Brainard, 2002). Chapter 3 of this thesis tested whether observers use information about the illumination present in a scene to obtain colour constancy and we were unable to find evidence for this hypothesis.
Chapter 4 examined whether subjects use explicit estimates of the illuminant's chromaticity in order to obtain colour constancy. We showed that this was not the case. Another important question is how the different psychophysical measuring methods tap into the underlying perceptual processes. These are all fundamental questions.

What is colour constancy?

But let us start with the most basic question of all: What is colour constancy and what was it 'designed' to do? We can assign constant colours to objects in order to support identification of objects in the environment (Gegenfurtner & Rieger, 2000; Wichmann et al., 2002). Without our ability of colour constancy this would be a problem. But for recognizing objects based on their colours, our visual system does not need to discount the illuminant completely, if only it can, for example, tell us which fruits are ripe. Colour constancy is typically studied in the laboratory with the use of simulated two-dimensional uniform surfaces under spatially uniform illumination, in asymmetric matching paradigms in which observers simultaneously view two scenes with two different illuminations. But, in the natural world, colours of objects under different light sources are rarely compared in this way. Instead, colour constancy will typically rely on colour memory: colours of objects must be compared to remembered colours to be judged as being the same or different, under changes in illumination and context that typically take place over minutes, hours, or days. But if recognizing and discriminating objects is the main aim of our visual system, why are we not asking subjects to recognize different coloured objects under different kind of illuminants, which is what our colour system was designed to do?

This was exactly the question that we asked our subjects in the study described in chapter 2 of this thesis. We asked subjects to name the colours of several test papers, which they had to learn beforehand, under different illuminations. We showed that subjects' performance under very natural conditions was good enough for recognizing objects under changes in illumination. This seems to be in line with our intuitive idea that we are colour constant in our daily life. Thus under natural circumstances, colour constancy seems to be a robust phenomenon. In the remaining chapters of this thesis, we tried to explain which factors could explain colour constancy, or which factors are important.

It seems that most subjects can respond in two different colour constancy modes and that most subjects can switch between these two modes of responses as a result of experimental instructions; When making an 'appearance match', subjects are instructed to make the reference and the test colour look identical in hue and saturation (Arend & Reeves, 1986; Arend et al., 1991; Troost & de Weert, 1991). In this case, weak colour constancy is obtained. When making a 'paper match' (sometimes called 'a surface match'), subjects are instructed to adjust the colour of the test in a way that it appears to be cut from the same piece of paper as the reference and they are therefore explicitly instructed to ignore the effect of the illumination (Arend & Reeves, 1986; Arend et al., 1991; Troost & de Weert, 1991; Cornelissen & Brenner, 1995; Bauml, 1999). Paper matches are approximately colour constant in some subjects. Thus, while subjects perceive a shift in surface colour as a result of a change in illumination (appearance matches), they are still able to estimate what the surface colour should be (paper matches). These results run parallel to our phenomenological experience in our daily lives; objects' colours change as a result of changes in illumination. However, as already pointed out, this is insignificant as the main aim of our visual system is to recognize objects. Making paper matches would therefore be better suited to test this daily ability than appearance matches do. Thus, when a colour researcher is more interested in the extent to which subjects are able to discount the illuminant, making appearance matches would be the best solution. On the other hand, if one is mainly interested in our daily ability to recognize objects on the basis of their colour, making paper matches has the largest ecological validity. Chapter 6 of this thesis points out that although there indeed seems to be a fundamental difference between matching either surface reflectance or matching reflected light, subjects cannot freely choose which to match.

In chapters 4 and 5 of this thesis, subjects had to match the colour of the paint in which several wooden plates were dyed. The plates were embedded in different scenes. In chapters 2 and 6, subjects had to match the colour of several coloured papers. These tasks resemble paper matches, as subjects have to infer what the colour of the object really is and not what the colour of the object is as they see it.

What is the most appropriate stimulus to use?

Another critical issue in colour constancy research is which kind of stimulus to use. Traditionally, colour constancy experiments have used very simple stimuli, typically a few diffusely illuminated surfaces (either real or simulated) arranged perpendicular to the line of sight (e.g., Mondrian stimuli). These two- dimensional stimuli do not resemble real surfaces. Object surfaces differ in how they absorb and reflect light. In general, reflection depends on the angle of the incident light and the angle from which one views the surface and the three-dimensionality of an object or scene (Foley et al., 1990). Mondrians are impoverished stimuli as they lack most of these visual complexities or sources of information. As it is useful to simplify and neglect geometric considerations when doing colour constancy experiments, it is important to realize that the assumptions of the 'Mondrian world' may not hold for surfaces perceived in the real world. Over the past several years, there has been an increase of interest in expanding the conceptualization of this area to incorporate effects that emerge only for complex, three-dimensional scenes. For example, recent studies have focused on how well vision compensates for changes in surface orientation (Boyaci et al., 2003; Ripamonti et al., 2004), how effectively it discounts inter-reflections between nearby surfaces (Bloj, Kersten & Hurlbert, 1999; Doerschner, Boyaci & Maloney, 2004; Delahunt & Brainard, 2004b) and how the visual system effectively estimates the spectral properties and spatial aspects of the illuminant in three-dimensioanl scenes (Kraft & Brainard, 1999;

Yang & Maloney, 2001; Boyaci, Maloney & Hersch, 2003; Bloj et al., 2004; Boyaci, Doerschner & Maloney, 2004; Khang & Zaidi, 2004). These results support the claim that the visual system effectively estimates the spatial and chromatic properties of the illuminant, perhaps by looking at specular highlights, shadows etcetera. However, these effects can be quite small or even absent (see Kraft & Brainard, 1999 and chapters 3 and 4 of this thesis). Moreover, even when an effect of the spatial layout on objects' colour perception can be measured, it is still unclear how these results could be explained.
Thus, although progress has been made in colour constancy research by using more sophisticated, complex, three-dimensional scenes, in terms of explanatory power these studies have added little. In this thesis, we have mainly used real three-dimensional scenes to create natural conditions for estimating surface colours.

Colour constancy as a 'binding problem' of cues.

It is likely that the visual system makes use of several sources of information, as the reliability of discounting the illuminant component becomes larger when several sources of information are taken into account. Much of the current work on colour constancy aims to discover what weights the visual system gives to different cues under different natural circumstances. For example, Kraft & Brainard (1999) used real objects and 'silenced' some of the individual cues. Their subjects exhibited poorer and poorer constancy as cues were successively reduced. However, Maloney (2002) stresses a possible complication, for the human visual system may dynamically assign different weights to different cues, depending on which cues are available or on the basis of task demands or prior knowledge. When the scene is rich in reliable cues, eliminating one of these cues may have little effect on the illuminant estimate since the shortfall may be taken up by the remaining cues. There is empirical proof that this is indeed the case (Kraft et al., 2002). In chapters 5 and

7 of this thesis we showed that the Grey World Hypothesis and luminance-colour correlations, respectively, are unlikely to be used by the visual system in order to estimate the illuminants' chromaticity. However, we cannot generalize our results to other scene displays as other scenes could contain extra cues which would lead to assigning different weights to the cues under study (luminance-colour correlations and the average chromaticity of a scene). How the visual system combines these cues in order to obtain colour constancy remains unresolved. Some authors (Maloney, 2002) claim that this cue integration of illuminant cues seems to dependent on the stimulus itself (see also Brenner, Granzier & Smeets, 2007). Chapter 3 of this thesis contradicts these findings by showing that the visual system does not seem to make a sophisticated analysis of the possible illumination in order to obtain colour constancy. In conclusion, the study of colour constancy is complicated by that the fact that the visual system can use some cue under condition A but not in condition B. Why and how the visual system assigns different weights to these sources of information as a result of different conditions remains unresolved. The studies described in this thesis show that each cue or information regarding the illumination is assigned a low weight, but that the combined sources of information make colour constancy a robust phenomenon.

What is estimated in colour constancy?

Some authors have elaborated models of observer performance for tasks where surface colour is judged (e.g., Speigle & Brainard, 1996; Brainard, Brunt & Speigle, 1997, Brainard, Wandell & Chichilnisky, 1993). In such models, the observer is assumed to be correctly performing a constancy computation (discounting the illuminant), with the one exception that their estimate of the illuminant deviates from the actual illuminant. Thus, a subject's performance that deviates from perfect colour constancy is explained by an erroneous estimate of the illuminant. This idea is related to the Illuminant Estimation Hypothesis, which states that the visual system makes an estimate of the illuminant and uses this estimate to calculate a surface' reflectance.

However, there is reason to believe that the visual system does not need to infer the illuminant's colour to achieve colour constancy; It has been known for a number of years that observers perform nearly as well when performing a matching task containing only two samples of spectral reflectances, as they do with scenes containing many samples (Blackwell & Buchsbaum, 1988; Arend et al., 1991), suggesting that performance in such task is mediated by illuminant-independent strategies (e.g., colour contrast) rather than by a process of illuminant estimation and subsequent discounting (e.g., Foster & Nascimento, 1994). Indeed, Amano et al., (2006) show that accurate judging of surface colours, by using two-surface-colour matching, in natural scenes seems to be independent of an explicit illuminant cue (cf. Yang & Maloney, 2001; see also Amano et al., 2005). Moreover, de Almeida et al. (2004) found that the errors in colour matching that observers made were independent of the extent of the illuminant change and these authors concluded that colour constancy is therefore illuminant independent. These illuminant-independent results are consistent with those obtained in an achromatic locus experiment (Brainard, 1998) for illuminant changes out of the daylight locus. Finally, Nascimento et al., (2004) did not find an effect of scene complexity on colour constancy using real scenes in which observers had to make discriminations between illuminant and material changes, which led them to conclude that local cues are the dominant cue for obtaining colour constancy. These results are in line with chapters 3 and 4 of this thesis, in which it is shown that adding illuminant cues does not enhance chromatic induction and that an explicit estimate of the illuminant's colour cannot explain the variation in colour constancy performance, respectively.

As has been argued elsewhere (Foster, 2003) a possible explanation for the insensitivity of surface colour judgements to information about the illuminant in a scene is observers' use of relational color constancy (Foster & Nascimento, 1994). This refers to the constancy of perceived colour relations between surfaces under different illuminants, as dinstinct from colour constancy, which refers to the constancy of perceived colours of surfaces. Thus, when discriminating between illuminant and material changes in scenes, observers simply compare how the colour of the test surface relates to the colour of one or more other surfaces in the scene or to the scene as a whole. First under the first illuminant and then under the second.

Another point of critique with respect to the Illuminant Estimation Hypothesis is of a theoretical nature instead of being data-driven; Explaning failures in colour constancy by suggesting that the illuminant was wrongly estimated is not a real explanation at all but is instead a circular reasoning; it is stated that colour constancy is poor when the illuminant is wrongly estimated and that the illuminant is estimated erroneously when colour constancy is poor. How and why the illuminant is estimated poorly under the experimental scenes under consideration remains unclear.

Colour constancy measured with different tasks

It has been assumed that stimuli having the same hue, saturation and lightness in different viewing contexts will match in appearance (Judd, 1940) and that a single perceptual representation underlies colour appearance and that when different appearance tasks tap this representation, the relation between the representation and the response is fixed. If this assumption is correct, then the effect of the context can be studied independently of the task (e.g., colour naming, colour matching achromatic adjustments). If this assumption is false however, then there are multiple perceptual representations of colour. The mapping between these internal colour representations and the stimulus would be different for each task, which would make generalizations between the different perceptual tasks troublesome.

A few studies have examined colour appearance using multiple methods. Troost and De Weert (1991) presented data that found higher degrees of constancy for a colour naming task than for a matching task. On the other hand, Speigle & Brainard (1996) used measurements of the shift in appearance between a bluish and a yellowish viewing context using real surfaces illuminated by real lamps. Observers indicated appearance using asymmetric matches, using a naming task, by adjusting stimuli to appear achromatic and by numerically scaling appearance. The shifts in appearance were in reasonable agreement across tasks for the observers, indicating that the effects of context on colour appearance are largely independent of the task used to assess appearance. Our results of chapters 5 and 6 are in line with the idea that there are multiple perceptual representations of colour and that different tasks tap one of these representations.

We argue that the amount of colour constancy obtained depend on many factors, such as the type of task that is used (e.g., achromatic settings, forced-choice matching etc) and on the visual cues which are present in a scene. We have shown that under natural viewing conditions, colour constancy can be very robust. Overall, it has become clear in this thesis that each visual cue alone adds only little in explaining colour constancy but that colour constancy is based on combining information from all the cues present in the visual image.

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Samenvatting

Kleurkonstantie is het vermogen om objectkleuren als redelijk onafhankelijk van de spectrale samenstelling van de lichtbron te kunnen waarnemen. De studies die in dit proefschrift worden beschreven beogen te bepalen welke visuele cues of strategieen door het visuele system gebruikt worden om kleurkonstantie te bereiken. De experimentele methoden beslaan zowel de simulatie van lichtbron-object interakties op een gekalibreerde kleurenmonitor als ook het gebruik van echte voorwerpen.

Hoofdstuk 2 richt zich op het onderzoek of kleurkonstantie goed genoeg buiten het laboratorium is. Kleurkonstantie onderzoek uitgevoerd binnen het laboratorium toont een lage mate van kleurkonstantie aan. Door het gebruik van een forced choice taak vonden we dat kleurkonstantie goed genoeg was om de funktie uit te kunnen voeren waarvoor het ontwikkelt is; het ondersteunen van de identificatie van voorwerpen op basis van hun kleur onder veranderingen in verlichting.

In Hoofdstuk 3 hebben we onderzocht of een grotere mate van de lichtbron wordt genegeerd wanneer er direkte informatie ten aanzien van de lichtbron aan een scene wordt toegevoegd. Onze resultaten ondersteunen deze hypothese niet. We simuleerden een achtergrond dat verlicht werd door een diffuse lichtbron en een andere lichtbron met een andere golflengte, die 1 van twee disks belichtte die de proefpersonen moesten matchen. We vonden een erg bescheiden mate van kleurinductie.

Hoofdstuk 4 beschrijft een direkte toets van de ‘schatten van de lichtbron hypothese’ in het kleurendomein. Wij onderzochten of het matchen van de kleuren van lampen, die een echte scene verlichten, de kleurinstellingen konden voorspellen voor houten plankjes die in dezelfde scene stonden opgesteld. De hoofd voorspelling van de ‘schatten van de lichtbron hypothese’ is dat het visuele systeem eerst een inschatting van de lichtbron maakt en op basis van deze inschatting de reflectie eigenschappen van een oppervlak bepaalt door middel van het negeren van de kleur van de lichtbron. We vonden dat proefpersonen slecht waren in het inschatten van de kleur van de lichtbron. Hun inschatting van de kleur van de houten plankjes was veel beter dan hun inschatting van de kleur van de lichtbron. Op basis hiervan conkluderen wij dat proefpersonen geen gebruik maakten van hun inschatting van de kleur van de lichtbron om kleurkonstantie te bereiken maar dat ze gebruik hebben moeten maken van lichtbron onafhankelijke eigenschappen in de scene, zoals kleurkontrast.

In Hoofdstuk 5 hebben wij de Grey World Hypothese getoetst door proefpersonen te vragen om zowel de kleur en de helderheid van houten plankjes te matchen die in scenes stonden waarbij een Grey World Hypothese tot een verkeerde inschatting van de kleur van de plankjes zou leiden. Wij konden geen afwijking in kleurperceptie ten aanzien van de plankjes detecteren die door de Grey World Hypothese worden voorspeld. Wij konkluderen derhalve dat onze proefpersonen geen Grey World aanname hanteerden om kleurkonstantie te bereiken.

Hoofdstuk 6 probeert de verschillen in kleurinstellingen te verklaren, die gevonden werden in hoofdstuk 5, tussen kleuren matchen met behulp van een computer monitor en met behulp van echte gekleurde papiertjes (Pantone). We wilden onderzoeken of deze twee taken fundamenteel verschillende apecten van kleurperceptie meten en als gevolg hiervan onvergelijkbaar met elkaar zijn. Specifieker gesteld, zijn de kleurinstellingen die proefpersonen maken anders als zij weten dat ze kleuren matchen van uitgezonden licht (een lichtbron; computer monitor) of het licht matchen van gereflecteerd licht (echte papiertjes). We vergeleken kleur instellingen van kleuren die beide op een computer monitor werden gepresenteerd met die waarbij de kleuren werden aangeboden op papiertjes. Daarnaast vergeleken we deze kleurinstellingen met instellingen waarbij proefpersonen kleuren aangeboden op papiertjes moesten matchen met een computer monitor en vice versa. Onze hypothese was dat als er een fundamenteel verschil bestaat tussen het inschatten van gereflecteerd- en uitgezonden licht, dat de instellingen voor laatstvernoemde systematisch slechter moeten zijn. De kleurinstellingen van proefpersonen was specifiek slecht wanneer ze een kleur gepresenteerd op een monitor moesten matchen met een papiertje. Deze prestatie was slecht te noemen indien gekeken werd naar zowel de systematische fout als ook in termen van de variabiliteit tussen proefpersonen. Uit deze gegevens konkludeerden wij dat het licht matchen dat de ogen bereikt en het matchen van gereflekteerd licht inderdaad fundamenteel verschillend is, maar dat proefpersonen niet in staat zijn om vrijwillig te kiezen tussen deze twee aspekten van kleurperceptie.

Hoofdstuk 7 bestudeert of het visuele systeem luminantie-kleur korrelaties gebruikt om de kleur van de lichtbron te kunnen inschatten. We evalueerden dit door het vergelijken van verschillende gesimuleerde scenes die overeen kwamen op helderheid en kleur, maar waarvan de korrelatie tussen helderheid en kleur lokaal gemanipuleerd was. We vonden dat er inderdaad een afwijking in de waargenomen kleur was die tegengesteld was aan de kleur van de heldere oppervlakken, als gevolg van de gebruikte helderheid-kleur korrelaties. Echter, zowel de resultaten van de kleurenmatching als ook van het maken van achromatische instellingen tonen dat enkel de korrelatie binnen een visuele hoek van minder dan 1 graad van de target relevant is. Dus het is onwaarschijnlijk dat het visuele systeem de korrelatie tussen de helderheid en kleur gebruikt om de kleur van de lichtbron inteschatten, omdat deze strategie te lokaal in effect is om een onbetrouwbare inschatting van de kleur van de lichtbron geven.

Summary

Colour constancy is the ability to perceive object's colours fairly independently of the spectral composition of the illuminant. The studies comprising this thesis are directed at determining which visual cues or strategies are used by the visual system to obtain colour constancy. The experimental methods involve both the simulation of illuminant-object interactions on a calibrated colour CRT and using real scenes.

Chapter 2 focuses on testing whether colour constancy is good enough outside the laboratory. Studies of colour constancy when tested inside the laboratory have found low amounts of colour constancy. By using a method of forced choice we found that colour constancy performance was good enough for the task for which it was evolved; to support identification of objects on the basis of their colour under changes in illumination.

In Chapter 3, we tested whether a much larger amount of the illuminant would be discounted if adding direct information about the illuminant in a scene. Our results did not support this hypothesis. We simulated different textured backgrounds, which were illuminated both by an ambient illumination and a local lamp of a different wavelength. The local lamp illuminated 1 of two disks which subjects had to match in colour and luminance. We found very modest effects of chromatic induction (discounting the effects of the illumination), showing that the visual system is unlikely to use information with respect to the chromaticity of the illumination in order to achieve colour constancy.

Chapter 4 described a direct test of the 'Illuminant Estimation Hypothesis' in the chromatic domain. We tested whether subjects' colour matches of lamps illuminating a real scene could predict their colour matches for wooden plates embedded in the same scene. The main prediction of the Illumination Estimation Hypothesis is that the visual system first makes an estimate of the illuminant and then determines the surface' reflectances by discounting the illuminant's colour. We found that subjects were poor in estimating the colour of the illumination. Their colour matches for the colour of the wooden test plates was much better than would be predicted from their estimates of the illuminant's chromaticity. Therefore, we conclude that subjects did not use their estimates of the illuminant in order to achieve colour constancy but must have used illuminant invariant properties in the scene, like colour contrast.

In Chapter 5, we tested the Grey World Hypothesis by asking subjects to match the colour and luminance of wooden plates that were embedded in scenes for which a Grey World assumption would lead to erroneous estimates of the plates' colour. We did not find the biases in colour perception for any of the plates used that are predicted by the Grey World Hypothesis. Thus we can conclude that our subjects did not use a Grey World assumption in order to obtain colour constancy.

Chapter 6 dealt with trying to explain the differences in colour settings found between colour matching with a CRT and matching with real coloured papers (Pantone Colour Specifier). We wanted to investigate whether subjects can distinguish between matching colours in terms of surface reflectance (real coloured papers) and in terms of reflected light (CRT). Subjects had to match the colour and luminance of several test papers embedded in a real scene, which was illuminated by a lamp. The test paper was either a real paper placed in front of the monitor or it was an image on a CRT that emitted the same CIE x, y, Y coordinates of the light as the test paper illuminated by the lamp. Subjects had to either match the test paper with a Pantone Colour Specifier or with an image on a CRT. We showed that performance was specifically poor when matching an image on a computer monitor to the colour of a piece of paper, both in terms of systematic errors and in terms of the variability between subjects. We proposed that matching the light reaching the eye and matching surface reflectance are indeed fundamentally different, but that subjects cannot freely choose which to match.

Chapter 7 tests whether the visual system uses luminance-colour correlations in order to estimate the illuminant's chromaticity. We evaluated this by comparing different simulated scenes with matched luminance and chromaticity, but in which the correlation between luminance and chromaticity was manipulated locally. We found that there is indeed a bias in perceived colour away from the chromaticity of bright surfaces. However, both the results of colour matching and of making achromatic settings show that only the correlation within less than 1° of the target is relevant. Thus, it is unlikely that the visual system uses the correlation between luminance and colour to determine the chromaticity of the illuminant, because this strategy is too local to give a reliable estimate of the illuminant's chromaticity.

The final chapter summarizes the main conclusions and offers some suggestions for future experimental tests and show what the main pitfalls for colour constancy research are.

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Curriculum Vitae

Jeroen Granzier werd op 15 juni 1977 geboren te Ohé en Laak (Limburg). Na het behalen van het VWO diploma aan het Bisschoppelijk College te Echt, ging hij in 1996 psychologie studeren aan de Universiteit Maastricht. Hij koos ervoor om gedurende 1 jaar twee stages te lopen. De eerste stage werd gedaan bij de vakgroep 'Neuropsychologie en Psychiatrie' in Maastricht en betrof psychofarmacologisch onderzoek bij mensen. De tweede stage werd aan dezelfde universiteit uitgevoerd bij de sectie 'Neuropsychologie en Psychobiologie' en betrof dier-experimenteel psychofarmacologisch onderzoek.
Na het behalen van zijn doctoraaldiploma in 2001 bleef hij werkzaam in Maastricht, maar nu als onderzoeksassistent waar hij taalonderzoek deed en experimenten uitvoerde op het gebied van verslaving.
In April 2003 begon hij als Assistant In Opleiding te werken aan het Erasmus Medisch Centrum te Rotterdam, waarvan dit proefschrift het resultaat is. Het laatste jaar van zijn promotieonderzoek werd uitgevoerd bij de faculteit bewegingswetenschappen aan de Vrije Universiteit te Amsterdam. In zijn vrije tijd is hij een fanatiek filmmaker van semi-professionele speelfilms. Per 1 juni werkt hij als statistisch onderzoeker bij het Centraal Bureau voor de Statistiek. Hij woont samen met zijn vrouw in Zuid-Limburg.

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