Introduction

Colour constancy, the stable perception of object colours under changes in the spectral composition of the illuminant, has been intensively investigated as it is a fundamental aspect of human perception in complex scenes (Shevell and Kingdom 2008). In spite of many different experimental approaches (for reviews see Foster 2003; Smithson 2005), it has been clearly demonstrated that colour-constancy levels can be high and almost perfect in some conditions (de Almeida et al 2004; Foster et al 1997, 2001a; Granzier et al 2009; Hansen et al 2007; Ling and Hurlbert 2008; Murray et al 2006).

As colour constancy implies to some degree segregation of light from material, it may depend on how efficiently the visual system can retrieve information from the environment, and it is expected to be more efficient in real complex scenes where a diversity of cues to the illuminant are available (Kingdom 2008). The influence of specific factors has been tested, eg spatial and temporal contexts (Hansen et al 2007), scene complexity (Kraft et al 2002; Nascimento et al 2005), movement (Werner 2007), binocular disparity and specularity (Yang and Maloney 2001), number of illuminants (Yang and Shevell 2003), and some effects were found (Hansen et al 2007; Werner 2007; Yang and Shevell 2002, 2003) suggesting that color constancy is influenced to some extent by contextual cues. However, although colour perception is known to be influenced by the perception of the dimensionality of the stimuli (Bloj et al 1999; Ling and Hurlbert 2004; Shevell and Miller 1996; Yamauchi and Uchikawa 2005), it is still not clear in which conditions depth perception influences colour constancy as the three-dimensional (3-D) structure was shown to affect performance in some experiments (Hedrich et al 2009; Werner 2006; Yang and Shevell 2002) but not in others (eg Amano et al 2002). These differences may be attributed to methodological issues probing different aspects of colour constancy (Foster 2003).

Colour constancy can be quantified by measuring the stability of colour percepts and therefore relies on some form of colour matching of a surface under different illuminations or, alternatively, it can be evaluated by setting the achromatic point under different illuminations (Smithson 2005). A more general notion of colour constancy refers to the relative judgments of paper matching, that is, the ability to identify a surface under
different illuminations regardless of changes in colour perception (Arend and Reeves 1986; Bäuml 1999; Craven and Foster 1992; Foster et al 2001a; Foster and Nascimento 1994). Under conditions of complete adaptation to the illuminant and with paper matching by memory (Hedrich et al 2009) or in a side-by-side paradigm (de Almeida et al 2004), colour constancy can be good and may be influenced positively by three-dimensionality of the scene. On the other hand, in real 3-D objects with fast illuminant changes, colour constancy varied little with scene chromatic structure and test object suggesting a predominant role of local versus more global cues (Nascimento et al 2005). Additionally, in an experiment in which flat surfaces were in different depth planes no influence of depth was found (Amano et al 2002).

The aim of this work was to carry out a direct test of the influence of 3-D structure of the scene on the degree of colour constancy under fast changes in the spectral composition of the illuminant. With an optical setup (de Almeida et al 2002; Nascimento et al 2002a) which allowed adjusting the colour of a single test object independently of the illumination of the scene in which the object was located, the effect of the 3-D structure was tested with two conditions: in a complex scene with real 3-D objects and in a real two-dimensional (2-D) scene made up of a flat collage of papers and fabrics identical to those that covered the 3-D objects.

2 Methods

2.1 Apparatus

Figure 1a shows the diagram of the optical setup. The virtual image of an illuminated test object, represented by a cube, is projected by a large 50/50 beam-splitter into a 3-D scene around the mask. The beam-splitter was a 400 mm × 300 mm borosilicate glass plate, 1 mm thick, with a Melles Griot HEBBAR coating. No secondary reflections from the back surface were visible. The scene was illuminated by a computer-driven liquid crystal display (LCD) data projector (Epson EMP-5600; 2200 ANSI Lumen) and the test object was illuminated independently by another LCD data projector (Sony VPL-CS10) driven by a visual stimulus generator VSG2/5 (Cambridge Research Systems) with 8-bit resolution in each of the R, G, and B signals. Figure 1b shows a 3-D scene viewed from the observer's point of view but without the beam-splitter. The black cube in the centre is the mask which had the same dimensions as the test cube and was placed in the exact position where the virtual image of the test cube was projected. It was darkened by candle smoke to avoid light reflected from the surrounding objects and background reaching the eyes of the observer. This 3-D carbon mask reflected only 0.5% of the incident light. The same scene as viewed binocularly by the observers through the beam-splitter is shown in figure 2a. To reproduce realistic mutual illuminations, surfaces identical to the ones located in the scene surrounding the mask were positioned near the test object, such that it had the same appearance as if it had been located in the scene. The accuracy of the procedure was verified visually by comparing the appearance of the virtual object with that of a second, identical, object placed close to the mask and under the same illuminant. The test cube seen in figure 2a was perceived in the scene as if it had been a real object and could not be distinguished from the other objects in the scene.

We used the same configuration in the 2-D scene. Here, a 2-D carbon mask was placed in the centre of a 2-D real scene exactly in the mask position and perpendicular to observer's viewing direction. The 2-D test object was placed in the test object location. Both 2-D carbon mask and 2-D test object were flat with their outline shapes mimicking the outline contour of the cube. Subsequent uses of the expression ‘test object’ refers to both 2-D and 3-D versions, depending on the dimensionality of the testing scene.
Scenes

The two types of scenes tested are shown in figure 2. Scene 1 was 3-D with a complex surround made of saturated-colour objects, identical to the one reported by Nascimento et al (2005). Scene 2 was a 2-D collage of papers and fabrics whose outline shapes mimicked the outline contours of the 3-D shapes in its 2-D planar projection. Therefore, scene 2 lacked the binocular disparity and shading cues to the object shapes. The distance from the objects to the observer ranged from 2 m to 2.5 m; the carbon masks were at a distance of 2.25 m and the grey wall in the background was at a distance of 2.5 m. The complete scene subtended a visual angle between 11 deg and 14 deg and the test object subtended a visual angle of 1.5 deg.

Figure 2. [In colour online.] The two scenes tested. (a) Scene 1: three-dimensional scene with a complex surround made of saturated-colour objects and the virtual image of the red cube. (b) Scene 2: two-dimensional scene made of objects which are two-dimensional projections of the objects in the three-dimensional scene 1. As in the 3-D version (see figure 1b), a two-dimensional candle smoked mask was also placed in the centre of the two-dimensional scene. The picture shows the virtual image of the green 2-D test object.
The LCD data projector illuminated the scenes by simulating illuminants with CIE 1931 \((x, y)\) of \((0.250, 0.255)\) and \((0.310, 0.326)\), corresponding to correlated colour temperatures of 25 000 K and 6700 K, respectively. The overall intensity was such that luminance on a white sample of \(\text{BaSO}_4\) placed in centre of the scene was \(\sim 320 \text{ cd m}^{-2}\).

2.3 Objects

The 3-D objects in scene 1 were solids whose surfaces were covered with coloured paper or coloured tissue. The objects in scenes 1 and 2 were covered with identical materials. The background wall was grey. The test objects were painted in black and covered with coloured papers. The colours of these papers could be red, green, yellow, or white, and were chosen to represent different hues, but such that they could not be easily identified with any of the other colours in the scene (Foster et al 2001a).

Therefore, we used eight test objects: four coloured cubes and four coloured flat objects that mimicked the outline contours of the four coloured cubes in their 2-D planar projection. Because non-standard papers were used, a correspondence between their tristimulus coordinates and Munsell notation could be useful. The red, green, and yellow papers were close to 10.0R 7/8, 10.0GY 6/6, and 2.5Y 7/6, respectively. Figure 3 represents, in CIE 1976 \((u', v')\) notation, the chromaticity coordinates of objects in the scene and of the test objects when illuminated under CIE standard illuminant D65. The luminance values of the 2-D test objects and of the illuminant with CCT 6700 K were 174, 212, 253, and 201 cd m\(^{-2}\), for the red, green, yellow, and white, respectively; for the illuminant with CCT 25 000 K they were 163, 217, 246, and 200 cd m\(^{-2}\). The cube was counterclockwise rotated 25.5\(^\circ\) with respect to the orthogonal illuminant direction. Therefore, the luminance of the frontal and left-side surfaces of the cube were those of the 2-D test objects multiplied by the factors 0.90 and 0.43, respectively.

![Figure 3](image)

**Figure 3.** Chromaticity coordinates in the CIE 1976 \((u', v')\) of the coloured surfaces used in the scene when illuminated under CIE D65.

2.4 Procedure

In each trial, the illuminant of the scene changes abruptly from 25 000 K to 6700 K at 1 s intervals. The time interval for each illuminant was signalled by a specific sound and the observer had to respond during the interval corresponding to 6700 K; failure to respond within that interval implied an immediate repetition of the trial. There was no time gap between trials. The illuminant of the test object changed either consistently or inconsistently with the scene illuminant by a variable amount quantified within the CIE 1976 \((u', v')\) colour space. Such sequential presentation under rapid illuminant change occurs in nature when a cloud passes in front of the sun (Foster et al 2001a).
In the consistent condition, the illuminants of the test object and of the scene were the same, that is \( I_1 \) was equal to \( I_2 \). In the inconsistent condition, when the scene was illuminated by the 25 000 K illuminant, both illuminants were the same, but when the scene was illuminated by the 6700 K illuminant, they were different. The test object illuminant was manipulated such that the colour of the test object could be any of 48 different colours defining a grid around the coordinates of the colour corresponding to the object illuminated by the 6700 K illuminant. The chromaticity coordinates of the test colours under the two illuminants and the corresponding test grid are shown in figure 4. The luminance of the colours in the grid was the same as the consistent colour of the test object and the grid spacing was always 0.005 units in the CIE 1976 \((u', v')\) colour space. In each trial, observers had to decide whether the paper making up the test object had changed or not. The responses were marked as ‘illuminant changes’ when the observers thought that the test paper had not changed, and ‘material changes’ when they thought that the test paper had changed. Both scenes were tested with the four test objects and the order of scenes and test objects was balanced over sessions. For a given scene, each test object was shown to each observer in about 1000 trials, running in 2 sessions \((2 \times 500)\) separated by several days. Therefore, each observer participated altogether in about 8000 trials in 16 sessions. A binomial distribution was assumed to represent the distribution of answers in a sequence of \( n \) independent trials with a probability of success estimated by the fraction of correct answers in each point of the testing grid. The exact number of trials \( n \) in each case was determined such that the standard error in the estimated probability was 0.2.

2.5 Calibration

The scene illumination was measured with a telespectroradiometer (SpectraColorimeter, PR-650; Photo Research Inc., California, USA) from the observer’s point of view throughout the beam-splitter and over a BaSO\(_4\) plug placed in front of the carbon mask. The settings of the scene illuminant were empirically adjusted to produce exactly 25 000 K and 6700 K. One cube and one square patch with identical dimensions of the face of the cube were made from the same material, namely a red, green, yellow, or white paper. The square patch was placed in front of the carbon mask and the tristimulus values (for the subsequent calibration of the test object) were measured under the two illuminants.

The calibration of the virtual image consisted of an empirical adjustment of the illuminant over the test object. Software written in MATLAB controlled both the PR-650 and the object illuminant through the VSG2/5 card. The procedure generated the 48 points of the testing grid (figure 4) and took about 15 min for each of the test objects. Maximum errors permitted in the displayed CIE 1976 \((u', v')\) were about a fifth of the grid spacing and about 2% in luminance.

2.6 Observers

Four observers participated of which three were naive (MR, PC, LP) and one (VA) was one of the authors of this work. Each had normal colour vision assessed by Rayleigh and Moreland anomaloscopy and the Farnsworth–Munsell 100-hue tests. Three observers were male, aged 23–33 years, and one was female, aged 41 years.

Figure 4 (see next page). Contour plots in the CIE 1976 \((u', v')\) space representing the response patterns for four coloured objects tested in the 3-D (left panels) and 2-D (right panels) scenes. Each panel represents the combined curves of equal probability for four observers. The circle in each graph represents the point of maximum probability. Open squares represent chromaticities of the test object under 25 000 K (lower), and 6700 K (upper) illuminants; solid symbols represent chromaticities of each point of the test grid.
3 Results

For each test object a probability map of correct answers was defined from the responses at each point of the test grid. Each map represents the combined curves of equal probability for four observers. The maximum in the probability map represents the point at which the observers judged the test paper to be of the expected chromaticity under the scene illuminant after the abrupt change. Figure 4 shows the contour plots in the CIE 1976 ($u', v'$) space representing the response patterns for the 3-D and 2-D coloured objects. The type of surface fitted to the data was a triangle-based linear interpolation which passes through the data points; the circle symbol in each map of figure 4 represents the maximum.

Colour constancy for each tested colour was determined as follows (Arend et al 1991). Let $a$ be the Euclidian distance from the chromaticity of each surface under 6700 K and the peak of the response distribution (the continuous line connecting open squares and open circles in figure 4) and $b$ be the Euclidian distance from the chromaticities of each surface under 6700 K and 25 000 K (the dashed lines connecting open squares in figure 4), then the constancy index $c$ can be computed as $c = 1 - a/b$. Constancy index ranges from 0 to 1 and perfect constancy produces $c = 1$, corresponding to the condition where the maximum of the response distribution coincides with the chromaticity of the surface under the 6700 K illuminant. Standard errors of constancy indices were computed from the two-dimensional standard deviation associated with the probability distribution of the responses.

Figure 5 shows the constancy indices for the four colours tested and for the two scenes. Indices varied with the colour of the test object from about 0.75 to 0.99 with an average value of 0.82, but did not vary significantly or systematically with the scene type. The values obtained are, in general, high, and globally of the same magnitude as those obtained by Foster et al (2001a). A repeated-measures ANOVA showed no significant effect of dimensionality of the scene ($F_{1,3} = 2.0$, $p = 0.2$), some effect of tested colours ($F_{3,9} = 5.2$, $p = 0.023$), and no interaction between the two ($F_{3,9} = 1.6$, $p > 0.5$).

4 Discussion

The main result of the experiment reported here is that observers’ performance is not affected by the dimensionality perceived on the scene. This is generally consistent with the results of other experiments with fast illuminant changes where constancy indices were little affected by scene structure (Nascimento et al 2005) and where the stimuli had components in different depth planes (Amano et al 2002).
Previous experiments that have found an effect of dimensionality of the scene on colour constancy used different experimental paradigms. Hedrich et al (2009) used a task in which observers viewed first a set of 2-D or 3-D coloured objects under one illuminant and later selected the 2-D coloured patch from a set illuminated by a different illuminant that best resembled in colour a specific test patch or object in the first scene. They found that constancy for the 3-D objects was better than for the 2-D surfaces. Memory effects were estimated in a preliminary experiment and they found that about 40% of the observers tested did not have adequate colour memory to do the task. Yang and Shevell (2002) adopted an achromatic task in which under each test illuminant observers adjusted the spectral composition of the test patch to appear white. The test patch could be perceived in 2-D or 3-D depending on stereo disparity. They found that colour constancy was higher for test patches perceived in 3-D. On the other hand, Kraft et al (2002), in a similar task but with real scenarios, found little effect of depth cues in colour constancy. Also using an achromatic task, Werner (2006) tested the effect of dimensionality by introducing stereo disparity in such a way that the test patch and background were perceived in the same or in different depth planes. An effect of depth was found, suggesting that constancy was less good when test and background were in different depth planes. The effects tested here and by Amano et al (2002) were almost immediate involving little or no memory load and did not rely on absolute judgments of white. These different methodologies may be probing different aspects of colour constancy and may weight in different degrees the relevance of depth cues.

Mutual reflections and stray illumination were completely absent in the 2-D condition. Although these cues may have been important in some experiments that used the manipulation of the scene geometry (Bloj et al 1999; Doerschner et al 2004), they did not seem to be critical here as constancy levels were similar in the 3-D and 2-D setups, the former involving complex illumination patterns and the latter using only direct illumination.

The constancy indices we obtained are similar to those reported by Foster et al (2001a), which suggests that monitor experiments might be as good for testing colour constancy under fast illuminant changes as are real scenes and objects. Consistently with previous findings (Nascimento et al 2005) the results showed only a small variation of the constancy indices with the colour of the test object. However, the corresponding contour maps of responses showed clear specificity for each test colour and are in close agreement with previous findings of anisotropic distributions of responses in colour space obtained with comparable experimental paradigms but with simulated CRT surfaces (Baraas et al 2004, 2006; Foster et al 2003).

Unlike in conditions with full adaptation to the illuminant (Hedrich et al 2009; Yang and Shevell 2002), the visual system seems insensitive to the three-dimensionality when the illuminant on the scene changes fast. Illuminant estimation can be carried out by automatic mechanisms that act locally over space (e.g. He and MacLeod 1998), or by local mechanisms that collate information over time which could be peripheral and/or central (de Almeida et al 2007; Smithson and Zaidi 2004). It is possible that, during fast illuminant changes, the ‘pop-out’ resulting from reflectance changes corresponds to a transient signal which is exploited by the visual system (Foster et al 2001b), and which is detected almost independently of the number of surfaces (e.g. Nascimento and Foster 2000). Discrimination of material changes from illuminant changes in this task may therefore depend on the extraction of a low-level transient signal generated in response to rapid changes in scene appearance. An evidence that the speed of change is important is that performance is progressively attenuated as changes occur more gradually (Linnell and Foster 1996). The transient signal may have its origin in a low-level signal based on the computation of spatial cone excitation ratios which
does not require illuminant estimation (Foster et al 2001b) and is therefore a local cue. These ratios change very little with changes in the spectral composition of the illumination (Foster and Nascimento 1994; Nascimento et al 2002b) and were shown to be relevant in the discrimination of material from illuminant changes (Nascimento and Foster 1997).

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