Colour-memory-dependent colour constancy: 2D vs 3D real surfaces

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Abstract

Perceived object colour tends to stay constant under changes in illumination. In the real world, assessing the constancy of object colours typically involves a comparison between the colour we see and the colour we remember; therefore, colour memory must play an important role in the phenomenon of colour constancy.

Here we describe two experiments investigating colour memory and colour constancy. Experiment 1 employs 3D domes as stimuli. In this experiment, using an artificial viewing environment with insufficient adaptation, we find a robust dependence of colour constancy on colour memory. This dependence cannot be captured by the most commonly used empirical measure of colour constancy, the Brunswik ratio, which does not incorporate colour memory and does not accurately reflect our findings in this experiment. We therefore develop a new colour constancy index (CCIm) which incorporates colour memory. Calculated in terms of CCIm, the results demonstrate that colour constancy is in fact moderate but imperfect in Experiment 1. Experiment 2 employs 2D natural papers. In this experiment, with longer adaptation time, under real illumination, the obtained CCIm results are all close to 1 (perfect colour constancy), indicating that colour constancy is as good as colour memory allows.

Introduction

Perceived object colour tends to stay constant under changes in illumination. This phenomenon is called colour constancy. Most previous colour constancy studies have employed the Brunswik (BR) ratio, or its close relative, as a measure of the degree of colour constancy [1-4]. The BR ratio is usually computed as:

$$BR = 1 - [(\text{perceptual shift})/(\text{physical shift})] \qquad (1)$$

where *'physical shift'* refers to the distance between the reference surface's chromaticities under the reference and test illumination, and the *'perceptual shift'* refers to the distance between the matched chromaticity and the reference surface's chromaticity under the test illumination. Perfect colour constancy would mean that the same surface is selected as a match under the test illumination (no perceptual shift) and $BR=1$; no colour constancy would mean that the subjects perform a match to the chromaticity of the reference surface under the reference illumination, i.e. a chromaticity match rather than a surface match (*perceptual shift = physical shift*) and $BR=0$. Experimentally measured colour constancy is generally not perfect, with BR indices ranging from 0.55 to 0.83, depending on the experimental conditions.

Most often, colour constancy is measured in asymmetric colour matching experiments, in which observers view two arrays of surfaces under two different illuminations side by side and make matches between them. Colour constancy in the real world is unlike such tasks, and instead typically involves a comparison between the colours we see and the colours we remember. Therefore, colour memory must play an important role in colour constancy, and moreover, measurements of colour constancy should take explicit account of memory. Some attempts have been made to investigate colour constancy using more natural experimental paradigms that encompass colour memory [5-6]. Recently, we have introduced a new colour constancy index (*CCIm*) that incorporates colour memory [7]. Here we use the *CCIm* to compare results from two constancy experiments using real stimuli in tasks requiring colour memory. Both experiments employ the 3D object illumination box developed by Ling and Hurlbert [8]. Seven colour-normal observers took part in both experiments.

Experiment 1. Colour memory and constancy for 3D domes

Experiment 1 investigates colour memory and colour constancy for 3D domes. Figure 1 illustrates a typical trial of the experiment. The observer pre-adapts to the reference display under the reference illumination for 50 sec, in which the dome appears neutral. After the adaptation period, the dome's surface colour appears for 5 seconds, during which time the observer has to memorise the colour. The illumination then changes to the test illumination and the central object appears neutral again for 10 seconds. After the 10 second delay, still under the test illumination, 5 alternative circular colour patches appear next to the central dome, and the observer must select from these the best match to the remembered colour.

We employed three standard daylight illuminations, at 4000-, 6500-, and 14500-K correlated colour temperature, labelled as D40, D65 and D145 respectively. D65 is always used as the reference illumination. In the pure colour memory condition, D65 is also the test illumination; in the constancy condition, the test illumination is either D40 and D145. We used three Munsell colours (2.5Y 8/4, 7.5P 3/6 and 10PB 2.5/4) as reference colours (labelled Y, P and PB, respectively). For each test illumination, five alternative colours are presented for each reference colour: the original reference colour as it would appear under the test illumination, and four alternatives (roughly equally spaced) varying along the line between the chromaticities of the reference colour under D145 and D40 in the CIE x, y diagram – close to the blue-yellow axis. Each reference colour is tested once under each test illumination. Trials are blocked by test illumination.

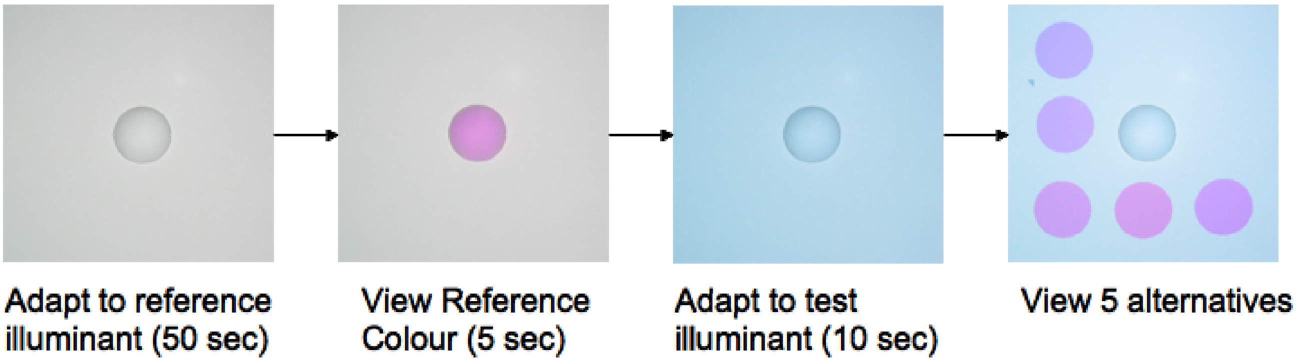

Figure 1. *The basic experimental paradigm for experiment 1.*

Results

Figure 2 illustrates the mean ΔE_{uv} memory shift for all reference colours, averaged across 7 observers. Here, a positive ΔE_{uv} difference indicates that the remembered colour shifts in a more 'yellowish' direction; a negative ΔE_{uv} difference indicates a memory shift in a more 'bluish' direction. Therefore, under no illumination change (D65), the colours are remembered as more saturated than the original colour. When the illumination shifts towards blue (D145), the memory shifts are significantly more yellowish than the shifts under no illumination change (D65); conversely, as the illumination shifts towards yellow (D40), the memory shifts are significantly more bluish.

Figure 2 demonstrates a clear dependence of colour constancy on colour memory. Under changing illumination, memory shifts always consist of two components, the pure memory shift (usually in the more saturated direction), and the constancy shift, derived from partial adaptation to the new illumination (usually in the opposite direction to the illumination change). Taking colour PB under D145 as an example, we see that there is almost no difference between the remembered and the original colour. The traditional BR ratio would therefore report almost perfect constancy ($BR \approx 1$). But if we compare PB's memory shift under D145 with its memory shift under D65, it is clear that they are significantly different, and that the illumination change has an indisputable effect on the remembered colour.

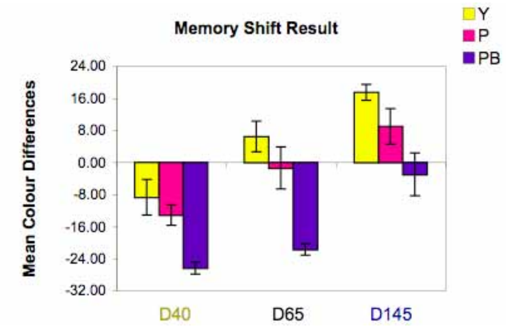

Figure 2. *Mean memory shift for all reference colours, averaged across 7 observers, measured in ΔEuv colour difference.*

Therefore, we analyse the results using the constancy index *CCIm*, which incorporates the effects of colour memory. We define *CCIm* as:

$$CCIm = 1 - \text{abs}[\,(\Delta E_C - \Delta E_P)/\ \Delta E_{\max}\,] \qquad (2)$$

where ΔE_C represents the combined memory shift (memory shift under changing illumination); ΔE_P represents the pure memory shift (memory shift under constant illumination), and $\Delta E_{\max}$ represents the range of available alternatives. Note that both ΔE_C and ΔE_P can take on positive or negative values, depending on the direction of the shift.

Table 1 lists the mean *CCIm* results for Experiment 1, for all reference colours, under D40 and D145 test illuminations, averaged across all 7 observers. These results demonstrate a substantial but imperfect degree of colour constancy.

Mean *CCIm*	Y	P	PB
D40	0.657	0.7064	0.8388
D145	0.6593	0.6629	0.6145

Table 1. *Mean CCIm results for Experiment 1, averaged across all 7 observers.*

Experiment 2. Colour memory and constancy for 2D papers

In this experiment, we examine colour memory and constancy for real 2D papers, printed by a characterised colour printer. The paradigm, illustrated in Figure 3, is similar to that of Experiment 1, but differs in the duration of the test illumination adaptation period (60 sec instead of 10) and in requiring the observer to perform mental arithmetic tasks during this period. For each of 13 reference colours, we present a distinct array of 16 test alternatives. For 7 reference colours, the alternatives vary only in saturation ('saturation' series) and for the other 6, the alternatives vary only in hue ('hue' series). In addition to the reference D65 and two test illuminations used in Experiment 1, we test one reddish illumination ('Red') and one greenish illumination ('Green'). Each reference colour/illumination condition is tested once per observer; trials are blocked by test illumination.

Results

Again, we analyse the results in terms of *CCIm*, which compares the colour memory shift under changing illumination to that under constant illumination. Here, for the normalising value in the denominator, we use the twice the maximum memory shift (combined or pure) taken over all observers, i.e.

$$\Delta E_{\max} = 2max_{observers}(\Delta E_C , \Delta E_P) \qquad (3)$$

Table 2 shows the mean *CCIm* results for each test illumination, averaged across all observers and reference colours, for the saturation and hue series separately. The *CCIm* values shown in this table are close to 1, indicating near perfect colour constancy. These results imply that the size and direction of the pure memory shift is nearly equal to that of the combined memory shift. In other words, changes in illumination do not affect substantially the size of the colour memory shift.

Illumination	D145	D40	Red	Green
Saturation Series	0.811	0.824	0.801	0.868
Hue Series	0.806	0.833	0.816	0.859

Table 2. *Mean CCIm for saturation series and hue series, averaged across all 7 subjects and reference colours within each condition, under test illuminations D145, D40, Red and Green respectively.*

Discussion and conclusions

The mean *CCIm* results for Experiment 2 indicate near perfect colour constancy, better than obtained in Experiment 1. The reasons may be as follows: (1) The longer reference viewing and adaptation periods in Experiment 2 may improve memory and allow a stronger contribution from chromatic adaptation to constancy. (2) In Experiment 1, the observer sees the 3D experimental object abruptly obtain its surface colour, and the test alternatives are obviously projected 2D colour patches. The observer may therefore be more likely to consider the colour stimuli not as real colour surfaces but as artificial simulations. Despite the solidity of the 3D objects, they may therefore be inclined to perform an appearance match instead of a surface match, resulting in poorer colour constancy [1,3].

In conclusion, we have demonstrated that for successive colour constancy tasks, the BR ratio is not an appropriate measure of colour constancy, as it does not take account of the effect of colour memory. Using a new index, the *CCIm*, which incorporates colour memory, we obtain moderate but imperfect colour constancy for real 3D domes with artificially applied surface colours. For real 2D colour papers with longer adaptation periods, the mean *CCIm* results are close to 1 (perfect colour constancy), indicating that colour constancy is almost as good as colour memory allows.

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Author Biographies

Yazhu Ling received a BSc in Computer Science from Southwest Jiao Tong University, an MSc in Colour & Imaging from the University of Derby, and a PhD in Psychology (2006) from Newcastle University, where she is now a postdoctoral research associate. Anya Hurlbert holds a BA in Physics (Princeton University), MA in Physiology (Cambridge University), MD (Harvard Medical School), and a PhD in Brain and Cognitive Sciences (MIT, 1989). She is Professor of Visual Neuroscience and co-Director of the Institute of Neuroscience at Newcastle University.

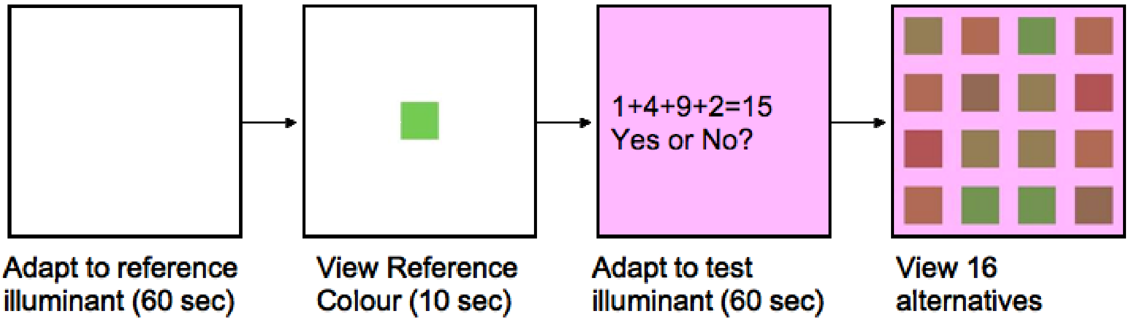

Figure 3. *The basic experimental paradigm for Experiment 2*