Perception, 2005, volume 34, pages 1007 – 1011

DOI:10.1068/p5185

Minimalist surface-colour matching

Kinjiro Amano, David H Foster
Computational Neuroscience Group, Faculty of Life Sciences, University of Manchester, Manchester M60 1QD, UK; e-mail: k.amano@manchester.ac.uk
Sérgio M C Nascimento
Department of Physics, Gualtar Campus, University of Minho, 4710-057 Braga, Portugal
Received 3 December 2003, in revised form 12 October 2004; published online 15 June 2005

Abstract. Some theories of surface-colour perception assume that observers estimate the illuminant on a scene so that its effects can be discounted. A critical test of this interpretation of colour constancy is whether surface-colour matching is worse when the number of surfaces in a scene is so small that any illuminant estimate is unreliable. In the experiment reported here, observers made asymmetric colour matches between pairs of simultaneously presented Mondrian-like patterns under different daylights. The patterns had either 49 surfaces or a minimal 2 surfaces. No significant effect of number was found, suggesting that illuminant estimates are unnecessary for surface-colour matching.

1 Introduction

How do we decide whether 2 coloured surfaces are the same when viewed under different lights? For uniform planar surfaces viewed in isolation in a dark field, the task is, of course, impossible: red paper in white light looks the same as white paper in red light. But when several differently coloured surfaces are present in the scene, the task of distinguishing the reflecting properties of a surface from the spectrum of the illuminating light becomes more feasible. If the gamut of surfaces in the scene is sufficiently large, then, in theory, it is possible to make a reliable estimate of the illuminant; for example, by assuming it coincides with a spatial average (Buchsbaum 1980), or with the highest-luminance surface (Land and McCann 1971), or by appealing to other statistical properties of the image (Finlayson et al 2001; Golz and MacLeod 2002). Knowing the properties of the illuminant then allows its effects to be discounted. Accordingly, experimental tests of observers' ability to match surfaces under different lights ('asymmetric colour matching') have often used stimuli consisting of patterns of many differently coloured surfaces. But do observers really need to estimate the illuminant in order to make surface-colour matches?

A crucial test of the role of the illuminant is whether asymmetric colour matching is worse when the illuminant cannot be reliably estimated; for example, when there are just 2 surfaces present in a scene. Previous experiments with stimulus patterns consisting of just a few surfaces (Arend et al 1991; Tiplitz Blackwell and Buchsbaum 1988; Valberg and Lange-Malecki 1990) have suggested that pattern complexity is not necessary for surface-colour matching, but the interpretation of these results in the present context is complicated by design issues; for example, differences in the geometry of the patterns. A direct comparison of the effects of the number of surfaces has been reported in an unpublished PhD thesis by one of the present authors (Nascimento 1995), but this was in a different task—that of discriminating illuminant changes on a pattern from changes in spectral reflectance (Craven and Foster 1992; Nascimento and Foster 1997). In the experiments reported here, therefore, observers made surface-colour matches between patterns of 49 surfaces, in Mondrian-like arrays, and between patterns of 2 surfaces, with each surface of the same size or with each pattern of the same area. No significant effect of number of surfaces was found.

2 Methods

2.1 *Stimuli*

The stimuli were simulations on a computer-controlled colour monitor of illuminated Lambertian coloured surfaces drawn randomly from 1269 samples in the *Munsell Book of Color* (Munsell Color Corporation 1976). (All subsequent references to surfaces and illuminants should be taken to refer to the corresponding simulations.) The surfaces were formed into patterns with three geometries: (a) 1×2 array of abutting square surfaces each of side 1 deg of visual angle; (b) 1×2 array of abutting surfaces each 3.5 deg $\times$ 7 deg; and (c) 7×7 array of abutting square surfaces each of side 1 deg (see figure 1). The random sampling producing each pattern was repeated, if necessary, to eliminate any accidental similarities between the test surfaces and the surrounding surfaces (Foster et al 2001). Fresh random samples were drawn in each trial. The patterns were viewed simultaneously side-by-side in a darkened room.

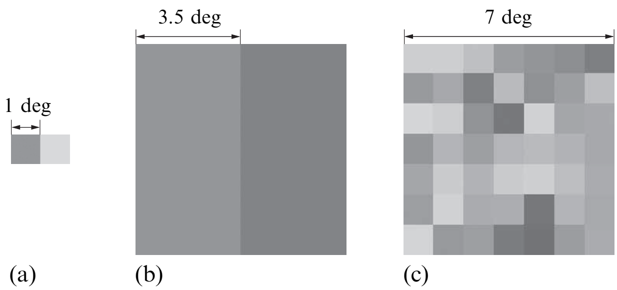

Figure 1. Stimulus patterns comprising (a) 1×2 surfaces each of side 1 deg of visual angle, (b) 1×2 surfaces each 3.5 deg $\times$ 7 deg, and (c) 7×7 surfaces each of side 1 deg, all drawn from the *Munsell Book of Color* (Munsell Color Corporation 1976). A colour version of this figure can be viewed on the *Perception* website at http://www.perceptionweb.com/misc/p5185/.

Patterns were presented in pairs. The left pattern was presented under a fixed spatially uniform daylight of correlated colour temperature 25 000 K and luminance 50 cd m^{-2}. The right pattern was identical but presented under a fixed spatially uniform daylight of correlated colour temperature 6 700 K and luminance 50 cd m^{-2}, except for the test surface. The test surface coincided with the right surface of the 2-surface pattern and with the centre surface of the 49-surface pattern. The illumination on the test surface was replaced by an independent, adjustable, spatially uniform local illuminant constructed from daylight spectral basis functions (Judd et al 1964). By varying the coefficients of these functions with a joypad input control to the computer, the observer could vary the chromaticity and luminance of the local illuminant, and therefore that of the test surfaces (Foster et al 2001). The three different pattern geometries were used in separate experimental sessions. The luminance of light reflected from the patches varied from 2.7 to 23 cd m^{-2}, with mean approximately 10 cd m^{-2}. The patterns were viewed binocularly at 100 cm.

2.2 *Apparatus*

Stimuli were generated by a computer-controlled RGB colour-graphics system with nominal 15-bit intensity resolution on each gun (VSG 2/3F, Cambridge Research Systems Ltd, Rochester, Kent, UK), and displayed on a 20-inch RGB monitor (GDM-20SE2T5, Sony Corp., Tokyo, Japan). Screen resolution was 1024×768 pixels and refresh rate approximately 100 Hz. A telespectroradiometer (SpectraColorimeter, PR-650; Photo Research Inc., Chatsworth, CA, USA), which had previously been calibrated by the UK National Physical Laboratory, was used to calibrate the display system. Errors in the displayed CIE (x, y, Y) coordinates of a white test patch were < 0.005 in (x, y) and $< 3\%$ in Y ($< 5\%$ at lower light levels).

2.3 *Procedure*

The observer's task was to adjust the chromaticity and luminance of the local illuminant on the test surface so that the patterns in each pair looked as if they were made from exactly the same pieces of coloured paper, that is, a 'paper match' (Arend and Reeves 1986). Observers were allowed to move their eyes freely (Cornelissen and Brenner 1995), and were given unlimited time to make each match. In all, they made sixteen matches in each experimental condition.

2.4 *Observers*

Six observers participated in the experiments, four male and two female, aged 22–37 years, each with normal colour vision, verified by Rayleigh and Moreland anomaloscopy, and with normal visual acuity. All except one, coauthor KA, were unaware of the purpose of the experiment.

3 Results

To quantify observers' surface-colour-matching performance, a numerical constancy index was used (Arend et al 1991). Thus, in the three-dimensional CIE 1976 $L^*u^*v^*$ colour space, let a be the distance between the observer's match and the 6700 K illuminant and let b be the distance between the 25000 K and 6700 K illuminants; then the constancy index is $1 - a/b$. Perfect constancy corresponds to an index of unity.

Values of the constancy indices averaged over the six observers are given in table 1 for three stimulus geometries (similar values were obtained with constancy indices based on an alternative CIE $L^*a^*b^*$ space). An analysis of variance showed that there was no significant effect of number of surfaces ($F_{2,10} = 0.5$, $p > 0.5$). There was also no significant effect of surface size with the 2-surface patterns ($F_{1,5} = 1.8$, $p = 0.2$).

Table 1. Surface-colour matching with three different stimulus geometries under daylights of correlated colour temperatures 25000 K and 6700 K. Constancy indices were calculated for CIE 1976 $L^*u^*v^*$ colour space. Data for six observers. Values in parentheses are those of 1 SEM.

	Stimulus geometry		
	2 surfaces 1 deg × 1 deg	2 surfaces 3.5 deg × 7 deg	49 surfaces 1 deg × 1 deg
Mean constancy index	0.72 (0.04)	0.78 (0.04)	0.73 (0.07)

4 Discussion

Values of the constancy index were similar to those reported previously (Bäuml 1999; Brainard et al 1997; Foster et al 2001) and, critically, there was no effect of number of surfaces: observers' matches were just as good with patterns of 49 surfaces as with patterns of 2 surfaces of the same size. Since it is impossible to make a reliable estimate of the illuminant from just 2 surfaces, it seems unlikely that observers need this information to make surface-colour matches. This result is consistent with a previous unpublished report (Nascimento 1995) on the discrimination of illuminant changes from spectral-reflectance changes with patterns of 2 surfaces. It is also consistent with previous studies (Arend et al 1991; Valberg and Lange-Malecki 1990; Werner et al 2000) on the effects of 'equivalent surrounds', although the issue of surround structure is complex (Brenner and Cornelissen 1998; Brenner et al 2003; Jenness and Shevell 1995; Monnier and Shevell 2003; Shevell and Wei 1998; Wachtler et al 2001).

How, then, do observers make matches with these minimal 2-surface patterns? One possibility is that they make use of 'relational colour constancy' (Foster and Nascimento 1994), which refers to the constancy of perceived colour relations between surfaces under different illuminants, as distinct from colour constancy, which refers to the constancy of perceived colours of surfaces. That is, in these matches, observers simply compare how the colour of 1 surface relates to the colour of 1 or more other surfaces or, indeed, to the pattern as a whole, first under the one illuminant and then under the other. There is a ready physiological substrate for these comparisons: the ratios of cone-photoreceptor excitations generated in response to light reflected from pairs of surfaces or groups of surfaces. Such ratios, which can also be calculated across postreceptoral combinations and spatial averages of cone signals, have the remarkable property of being almost exactly invariant under changes in illuminant, both with coloured papers (Foster and Nascimento 1994) and with natural surfaces (Nascimento et al 2002). Importantly, these ratios do not require an estimate of the illuminant or, indeed, of the spectral reflectances of individual surfaces in the patterns (Nascimento 1995).

This is not, of course, to imply that colour constancy is solely a cone-based phenomenon or that observers never make estimates of the illuminant when that information is available. Rather, as has been argued elsewhere (Foster 2003), since only perceived colour relations and not perceived colours need to be preserved to succeed at asymmetric colour matching, such measurements do not themselves properly limit colour constancy.

Acknowledgments. This work was supported by the Biotechnology and Biological Sciences Research Council under grant S08656 and the Engineering and Physical Sciences Research Council under grant GR/R39412/01.

References

Arend L, Reeves A, 1986 "Simultaneous color constancy" *Journal of the Optical Society of America A* **3** 1743 – 1751

Arend L E Jr, Reeves A, Schirillo J, Goldstein R, 1991 "Simultaneous color constancy: papers with diverse Munsell values" *Journal of the Optical Society of America A* **8** 661 – 672

Bäuml K-H, 1999 "Simultaneous color constancy: how surface color perception varies with the illuminant" *Vision Research* **39** 1531 – 1550

Brainard D H, Brunt W A, Speigle J M, 1997 "Color constancy in the nearly natural image. 1. Asymmetric matches" *Journal of the Optical Society of America A* **14** 2091 – 2110

Brenner E, Cornelissen F W, 1998 "When is a background equivalent? Sparse chromatic context revisited" *Vision Research* **38** 1789 – 1793

Brenner E, Ruiz J S, Herráiz E M, Cornelissen F W, Smeets J B J, 2003 "Chromatic induction and the layout of colours within a complex scene" *Vision Research* **43** 1413 – 1421

Buchsbaum G, 1980 "A spatial processor model for object colour perception" *Journal of the Franklin Institute* **310** 1 – 26

Cornelissen F W, Brenner E, 1995 "Simultaneous colour constancy revisited: an analysis of viewing strategies" *Vision Research* **35** 2431 – 2448

Craven B J, Foster D H, 1992 "An operational approach to colour constancy" *Vision Research* **32** 1359 – 1366

Finlayson G D, Hordley S D, Hubel P M, 2001 "Color by correlation: A simple, unifying framework for color constancy" *IEEE Transactions on Pattern Analysis and Machine Intelligence* **23** 1209 – 1221

Foster D H, 2003 "Does colour constancy exist?" *Trends in Cognitive Sciences* **7** 439 – 443

Foster D H, Amano K, Nascimento S M C, 2001 "Colour constancy from temporal cues: better matches with less variability under fast illuminant changes" *Vision Research* **41** 285 – 293

Foster D H, Nascimento S M C, 1994 "Relational colour constancy from invariant cone-excitation ratios" *Proceedings of the Royal Society of London, Series B* **257** 115 – 121

Golz J, MacLeod D I A, 2002 "Influence of scene statistics on colour constancy" *Nature* **415** 637 – 640

Jenness J W, Shevell S K, 1995 "Color appearance with sparse chromatic context" *Vision Research* **35** 797 – 805

Judd D B, MacAdam D L, Wyszecki G, 1964 "Spectral distribution of typical daylight as a function of correlated color temperature" *Journal of the Optical Society of America* **54** 1031 – 1040

Land E H, McCann J J, 1971 "Lightness and retinex theory" *Journal of the Optical Society of America* **61** 1 – 11
Monnier P, Shevell S K, 2003 "Large shifts in color appearance from patterned chromatic backgrounds" *Nature Neuroscience* **6** 801 – 802
Munsell Color Corporation, 1976 *Munsell Book of Color—Matte Finish Collection* (Baltimore, MD: Munsell Color Corporation)
Nascimento S M C, 1995 *Surface Colour Perception under Illuminant Transformations* PhD thesis, Keele University, Keele, UK
Nascimento S M C, Ferreira F P, Foster D H, 2002 "Statistics of spatial cone-excitation ratios in natural scenes" *Journal of the Optical Society of America A* **19** 1484 – 1490
Nascimento S M C, Foster D H, 1997 "Detecting natural changes of cone-excitation ratios in simple and complex coloured images" *Proceedings of the Royal Society of London, Series B* **264** 1395 – 1402
Shevell S K, Wei J, 1998 "Chromatic induction: border contrast or adaptation to surrounding light?" *Vision Research* **38** 1561 – 1566
Tiplitz Blackwell K, Buchsbaum G, 1988 "Quantitative studies of color constancy" *Journal of the Optical Society of America A* **5** 1772 – 1780
Valberg A, Lange-Malecki B, 1990 " 'Colour constancy' in Mondrian patterns: a partial cancellation of physical chromaticity shifts by simultaneous contrast" *Vision Research* **30** 371 – 380
Wachtler T, Albright T D, Sejnowski T J, 2001 "Nonlocal interactions in color perception: nonlinear processing of chromatic signals from remote inducers" *Vision Research* **41** 1535 – 1546
Werner A, Sharpe L T, Zrenner E, 2000 "Asymmetries in the time-course of chromatic adaptation and the significance of contrast" *Vision Research* **40** 1101 – 1113

ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

PERCEPTION

VOLUME 34 2005

www.perceptionweb.com